An Assessment of The Capabilities of The Infaunal Quality Index (IQI) To Detect Benthic Ecological Change Within Offshore Windfarm Developments

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Submitted to Swansea University in fulfilment of the requirements for the Degree of MRes Biosciences

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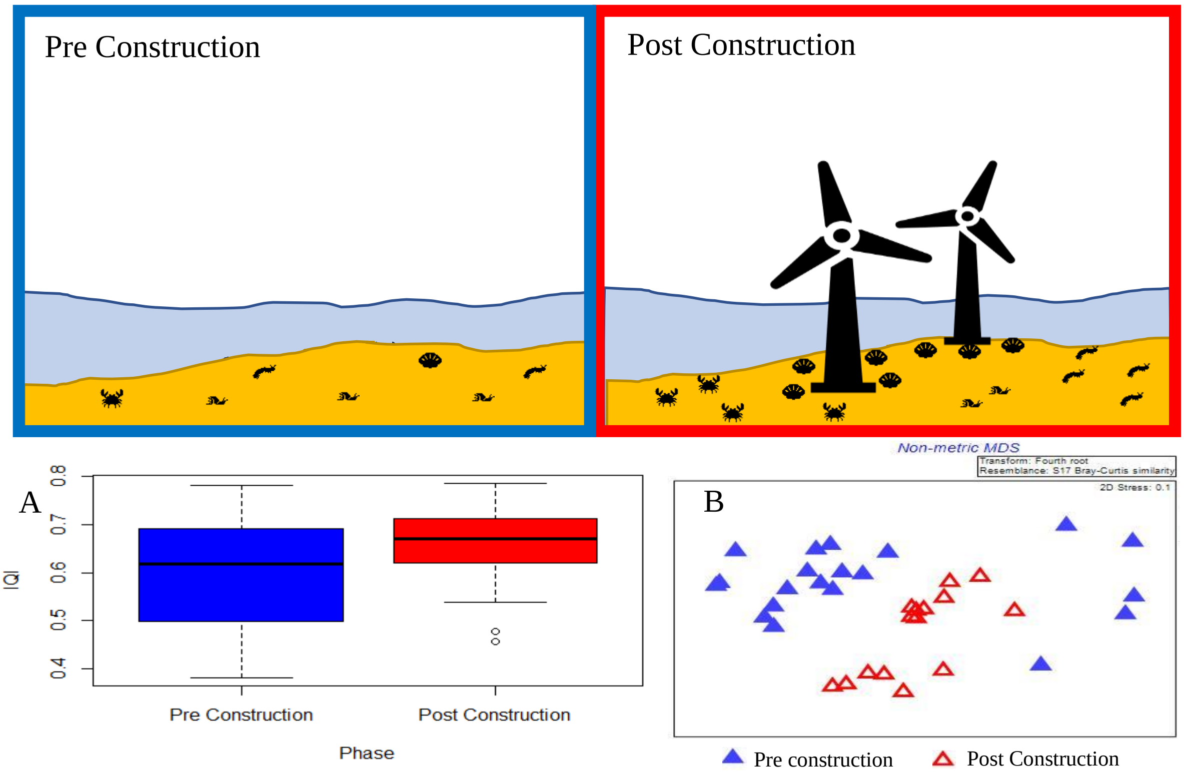
Abstract

Many governments are turning to renewable sources of energy to tackle the current climate emergency and ensure current and future energy demands are met. Offshore wind energy is one of the fastest growing areas of the energy sector, however with increasing areas of the ocean floor being used for wind and other structural installations, the need for effective environmental monitoring is crucial to ensure sustainable management of these sites. The Water Framework Directive (WFD) is one such monitoring strategy, which includes the Infaunal Quality Index (IQI) method which is used by the United Kingdom to monitor benthic community health within coastal and estuarine (transitional) waterbodies. There are, however, concerns around the IQI's capability to suitably detect ecological changes within areas modified by structures (such as wind turbine monopiles). Within this investigation the IQI waterbody assessment protocol was compared to multivariate community analysis to assess the IQI's ability to detect ecological change at near and far field waterbody levels within four windfarm development sites before and after windfarm construction. Findings from this investigation suggest the IQI failed to detect ecological change at a waterbody level with no significant change apparent, while multivariate community analysis found significant change at the same spatial and temporal scale. The suggested reasons for the IQI's inability to detect change in these circumstances are A change in habitat (sediment characteristics) driving community change will not be identified within the IQI model as the reference conditions within the model are derived from sediment characteristics; and the waterbody scale conflates impacted areas with non-impacted areas. Alternatives to the IQI in these scenarios and possible repercussions for these findings are discussed.

Lay Person Summary

The demand for energy is ever growing, to tackle the current climate emergency many governments are turning to renewable sources of energy to meet demands. Offshore wind energy is one of the fastest growing areas of the energy sector, however with increasing areas of the ocean floor being used for wind turbine placement, there is a need to ensure these structures don't damage surrounding seabed dwelling marine life. The Infaunal Quality Index (IQI) is used by the United Kingdom to monitor benthic community health within coastal and estuarine areas. There are, however, concerns around the IQI's capability to suitably detect ecological changes within areas containing structures (such as wind turbines). This investigation compared the IQI method against a group of other statistical tests commonly used to assess changes in biological communities (multivariate analysis) within four windfarm developments before and one year after windfarm construction. While the IQI method did not detect any change in seabed community before and after the wind turbines were constructed, a significant change in seabed community was detected within the windfarms using multivariate analysis (Box 1). The reasons for the difference in the ability of the two methods are suggested to be the scale of the area within the windfarm that was sampled, meant any change in seabed community close to the wind turbine may have conflated the areas further away from the turbines and not affected. Additionally, as the IQI method assesses seabed community health, while the multivariate analysis assesses community change, the change in community detected by multivariate analysis may not have been a change in community health, thus not detected by the IQI method. Finally, the equations within the IQI model uses values derived from the environment (seabed sediment and water salinity) to calculate the final IQI values, thus a change in environment derived values driven by the wind turbines may have negated any true change in benthic community health.



Box 1 A comparison between the Infaunal Quality Index (IQI) (A) and Bray Curtis dissimilarity based multivariate analysis (B) to identify benthic community change within offshore windfarm developments. Items coloured blue represent Preconstruction samples and environment. Items coloured red represent post construction samples and environment. Graph A is a boxplot which represents the spread of data within a distinct category, the bold line indicates the median value, the box represents the upper and lower quartiles, the outside lines represent the minimum and maximum values without outliers (defined as a data point that is outside 1.5 times the interquartile range above the upper quartile and bellow the lower quartile). Plot B is A 2D MDS plot represent as Bray-Curtis Dissimilarity matrix in 2-dimensional space, with a data point's distance from all other data points representing its dissimilarity. Points closer together have a greater similarity.

Declarations and Statements

I Declare that the work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

this thesis is the result of my own investigations, except where otherwise stated with other sources acknowledged.

I Saul Moore give consent for the thesis, if accepted to be made available online in the University's Open Access Repository and for inter-library loan, and for the title and summary to be made available to outside organisations

Name: Saul Moore

Signed: [redacted]

Date 20/04/2023

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The University's ethical procedures have been followed and, where appropriate, that ethical approval has been granted.

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Date..................... 20/04/2023..

Acknowledgements

I Wish to take this opportunity to acknowledge the support, and patience Dr Ed Pope has provided during the duration of this project, he has made the experience enjoyable.

Statement of Expenditure

Please note: This expenditure includes expenditure from a previous field based project which could not be completed due to experiment destruction, all expenditure is attributed to that project with only the Primer software used for this investigation.

Student Name: Saul Moore
Student Number: [redacted]
Project Title: An Assessment of The Capabilities of The Infaunal Quality Index (IQI) To Detect Benthic Ecological Change Within Offshore Windfarm Developments
And
Variation in Epifaunal Settlement and Succession on Marine Debris in Coastal Areas

[redacted]

I Hereby certify that the above information is true and correct to the best of my knowledge

[redacted] [redacted]

Signature (Supervisor) Signature (Student)

Statement of Contributions

Contributor Role	Contributors
Conceptualization	SM
Data Curation	SM
Formal Analysis	SM
Funding Acquisition	N/A
Investigation	SM
Methodology	SM
Project Administration	SM, ECP
Resources	SM, ECP
Software	SM.
Supervision	ECP
Validation	N/A
Visualization	SM
Writing – Original Draft Preparation	SM
Writing – Review & Editing	SM, ECP

Ethics Approval

Project Ethics Assessment Confirmation|Cadarnhad o Asesiad Moeseg Prosiect

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- MOORE S. [redacted]

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This is an automated confirmation email for the following project. The Ethics Assessment status of this project is: APPROVED

Applicant Name: Saul Moore
Project Title: Variation in Epifaunal Settlement and Succession on Marine Debris in Coastal Areas
Project Start Date: 27/01/2021
Project Duration: 7 months
Approval No: [redacted]

NOTE: This notice of ethical approval does not cover aspects relating to Health and Safety. Please complete any relevant risk assessments prior to commencing with your project.

Neges awtomataidd yw hon ar gyfer y prosiect canlynol. Statws Asesiad Moeseg y prosiect hwn yw: APPROVED

Enw'r Ymgeisydd: Saul Moore
Teitl y Prosiect: Variation in Epifaunal Settlement and Succession on Marine Debris in Coastal Areas
Dyddiad Dechrau'r Prosiect: 27/01/2021
Hyd y Prosiect: 7 months
Rhif y Gymeradwyaeth: [redacted]

SYLWER: Nid yw'r hysbysiad hwn o gymeradwyaeth foesegol yn cynnwys agweddau sy'n ymwneud ag Iechyd a Diogelwch. Dylech gwblhau unrhyw asesiadau risg perthnasol cyn dechrau eich prosiect.

Health and Safety and Risk Assessment

Collage: Science
Activity: Computer based work
Location: Home Office

Assessor: Saul Moore
Assessment Date: 01/06/2021

Hazards	Who might be harmed	Controls and Measures	S	L	Risk (SxL)
Slips and trips	All persons may be injured if they trip over objects or slip on spillages.	• General good housekeeping. • All areas well lit, including stairs. • No trailing leads or cables. • Keep work areas clear, e.g., no boxes left in walkways, deliveries stored immediately.	2	4	**8**
Display screen equipment	Persons risk posture problems and pain, discomfort or injuries, e.g., to their hands/ arms, from overuse or improper use or from poorly designed workstations or work environments. Headaches or sore eyes can also occur, e.g., if the lighting is poor.	• Workstation and equipment set to ensure good posture and to avoid glare and reflections on the screen. • Work planned to include regular breaks or change of activity. • Lighting and temperature suitably controlled. • Adjustable blinds at window to control natural light on screen. • Noise levels controlled.	1	4	**4**
Electrical	Persons could get electrical shocks or burns from using faulty electrical equipment. Electrical faults can also lead to fires.	• Any defective plugs, discoloured sockets or damaged cable/equipment should be identified. • Defective equipment taken out of use safely and promptly replaced.	4	1	**4**
Fire	If trapped, Persons could suffer fatal injuries from smoke inhalation/ burns.	• Identify fire risks. • Ensure smoke alarms are in working order. • Do not leave equipment on overnight. • Identify fire exit. • Keep fire exit clear	5	1	**5**
Lone working	Persons could suffer injury or ill health while working alone.	• Ensure colleague or next of kin have knowledge of daily plans. • Ensure communication (mobile phone) is always accessible	5	1	**5**
Cybercrime/ loss of personal data	Persons may have personal data stolen	Follow Swansea Universities Information Security Policy.	2	3	**6**

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Signature (Supervisor)

Signature (Student)

		Consequences (S)				
		1 **Insignificant** No injuries/ minimal financial loss	**2** **Minor** First aid treatment/ medium financial loss	**3** **Moderate** Medical treatment/high financial loss	**4** **Major** Hospitalised/ large financial loss	**5** **Catastrophic** Death/ Massive Finanical Loss
Likelihood (L)	**5** **Almost Certain** Often occurs/ once a week	5 Moderate	10 High	15 High	20 Catastrophic	25 Catastrophic
	4 **Likely** Could easily happen/ once a week	4 Moderate	8 Moderate	12 High	16 Catastrophic	20 Catastrophic
	3 **Possible** Could happen/ happen once a year	3 Low	6 Moderate	9 Moderate	12 High	15 High
	2 **Unlikely** Hasn’t’ yet happened but could happen	2 Low	4 Moderate	6 Moderate	8 High	10 High
	1 **Rare** Concievable but 1/100-year event	1 Low	2 Low	3 Low	4 Moderate	5 Moderate

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Abbreviation	Term
WFD	Water Framework Directive
IQI	Infaunal Quality Index
AMBI	AZTI Marine Biotic Index
RNAG	Reasons for Not Achieving Good ecological status
EG	Ecological Group
EQR	Ecological Quality Ratio
MMO	Marine Management Organisation
EMF	Electro Magnetic Field
CEFAS	The Centre for Environment, Fisheries and Aquaculture Science
RSMP	Regional Seabed Monitoring Programme
UKTAG	UK Technical Advice Group
NMBAQC	NE Atlantic Marine Biological Analytical Quality Control
WORMS	World Register of Marine Species
M-AMBI	Multivariate - AZTI Marine Biotic Index
SSI	Size Spectra Index
TOC	Total Organic Carbon

1.0 Introduction

1.1 Windfarm Futures

With the world's demand for energy growing and the movement away from traditional energy sources such as fossil fuels, many governments are looking to renewables to help fulfil current and future energy needs. Offshore wind energy has become prevalent in recent times, with global wind power capacity in 2011 estimated at 240 GW of which 2% was offshore wind energy (Kaldellis and Kapsali, 2013). Many of the world's offshore windfarms are located within the continental shelf of Northern Europe, due to its shallow seas and windy climate (Bilgili et al., 2011). As of 2020 112 offshore windfarms were active globally, with a further 712 projects in different stages of development (Díaz and Guedes Soares, 2020).

Within UK waters there were (as of 2020) 40 windfarms consisting of 2291 turbines, with an additional 8 wind farms (719 turbines) under construction (The Crown Estate, 2020) with a production capacity of 10.4 GW (13% of UK energy production (The Crown Estate, 2020). The UK government aims to increase offshore wind production to 40GW by 2030 under the "Net-Zero By 2050" plan (The Crown Estate, 2021).

1.2 Impacts from Windfarms

While wind energy is key to tackling the current climate emergency, there are many local ecological changes and short-term impacts caused by offshore windfarms. Acoustic disturbance during the construction phase of windfarm projects impacts many marine mammal species (Thompson et al., 2020); and the aerial structures have been found to displace diving seabirds such as Northern Gannets (*Morus bassanus*) (Garthe et al., 2017), while acting as artificial islands for other seabirds such as the European Cormorant (*Phalacrocorax carbo*) and the European Shag (*Phalacrocorax aristotelis*) (Dierschke et al., 2016). The introduction of hard structures within a normally soft sediment environment leads to an increase in epifaunal species in addition to many fish species (De Mesel et al., 2015; Degraer et al., 2020; Reubens et al., 2014; Vandendriessche et al., 2009).Furthermore the resuspension of sediment generated by turbulence and scour around turbines can lead to a localised reduction in primary productivity, through increased turbidity and lower light penetration (Galparsoro et al., 2022). Additionally, windfarms have been found to act as de-facto marine protected areas due to the introduction of undersea cables making destructive fishing methods such as bottom trawling and dredging not possible (Ashley et al., 2014; Coates et al., 2016).

1.3 Legislation and Monitoring

Under many licences provided to offshore wind projects by the Marine Management Organisation (MMO) licence holders are required to undertake a suite of environmental monitoring during the lifetime of the project from construction through operation and decommissioning, to assess any mitigation action required to lessen impacts to local ecosystems (Scott, 2010). One such environmental monitoring program is benthic community and sediment monitoring. Depending on the substrate and parameters of monitoring aims, methods for monitoring benthic community and sediment structure include grab sampling; dropdown video camera monitoring; and sidescan and multibeam bathymetry scanning (Chen and Tian, 2021; Hemery et al., 2022).

1.4 Benthos

The benthos represents communities of fish and invertebrates living as infauna within the sediment and on the surface of the seabed, in addition to the sediment habitat. This environment is vitally important for the fishing industry. Shellfish such as crustaceans and bivalves (Thrush et al., 1995), all dwell within or on the seabed. Additionally, many infaunal invertebrate species make up a large proportion of prey for other commercially important ground fish such as plaice (*Pleuronectes platessa*), flounder (*Platichthys flesus*) and sole (*Solea solea)* (Amara et al., 2001; Dolbeth et al., 2008; Vinagre et al., 2008).

It is estimated that approximately 2 Gt of atmospheric CO_2 is absorbed into the oceans each year (Falkowski and Wilson, 1992), of which up to 40% is sequestered into the sediment by photosynthetic organisms (Duarte and Cebrián, 1996; Turner, 2015; Zhang et al., 2017). Therefore, marine sediments represent a significant long-term store for atmospheric CO_2. Additionally, sediments represent a significant sink for heavy metals and pollutants within the marine environment, leading to a reduction in bioavailability of such compounds under stable conditions (Ansari et al., 2003; Bach et al., 2017; Wenger et al., 2017).

1.5 Impacts of Windfarms on the Benthic Environment

Windfarms have numerous impacts on the benthic environment during all stages of the project. During the construction phase pile driving during monopile installation and backhoe dredging during cable laying have been found to elicit a behavioural response from multiple species including blue mussels (*Mytilus edulis*), hermit crabs (*Pagurus bernhardus*) and European lobsters (*Homarus gammarus*) up to 500 m from the activity (Roberts and Elliott, 2017). Additionally, the dredging and laying of cables have been found to remove, damage and alter benthic habitats, temporarily increase turbidity and release buried pollutants (Taormina et al., 2018). During the operation of the windfarm the wind turbine structures have been found to alter the hydrodynamic environment of the surrounding area (van Berkel et al., 2020; Vanhellemont and Ruddick, 2014), subsequently altering the sediment environment within the windfarm (Coates et al., 2014).

The undersea power cables have been found to emit an electromagnetic field (EMF) which attracts taxa sensitive to EMF, including skates and other elasmobranchs, crabs, and other decapods (Hutchison et al., 2020; Scott et al., 2021). The act of dredging, and the hydrodynamic alterations attributed to marine structure installation also leads to a disturbance to the sediment which can resuspend organic matter, pollutants and heavy metals, allowing these compounds to disperse and become more bioavailable (Ansari et al., 2003; Bach et al., 2017; de Mora et al., 2004; Wenger et al., 2017).

1.6 Impacts on Benthic Ecology

Offshore wind turbines are commonly installed onto soft substrates. As the turbines are commonly made out of hard substrates such as steel (Anandavijayan et al., 2021), coupled with the rock reef created through sour protection, means the structures act as an artificial reef, allowing epilithic communities which are not normally found within soft sediment environments to develop, including Mytilidae beds, high abundances of Anthozoa, and the tube building amphipod *Jassa* (De Mesel et al., 2015; Maar et al., 2009). The rocky substrate of the scour protection also provides shelter for predatory fish species such as plaice, pouting, cod and flounder, which have been found to feed on epibenthic species (Amara et al., 2001;Buyse et al., 2022; Reubens et al., 2014b, 2011; Vinagre et al., 2008). A study by Elliot and Wilson ,2009 calculated the potential benthic habitat creation when installing wind turbines with gravel, boulder and synthetic frond scour protection, they found that both boulder and gravel scour protection methods led to a net increase in habitat of 650 and 577 m^2 respectively. Furthermore, Wilson et al.,2010 suggested that while a change in sediment characteristics and thus benthic community structure is likely within offshore windfarms, often these sites are placed in high current sandbank areas which naturally have a high temporal variation in community due to shifting sediments and thus the addition of anthropogenically derived sediment change will not be as pronounced than in more stable environments.

The laying of undersea power cables is undertaken using multiple site-specific methods including ploughing the seabed then backfilling and waterjet trenching. Both methods have been found to disrupt the surrounding benthic community in the short term with recovery taking from several weeks to 1-2 years for ploughed cables while waterjet burial recovery can take up to 8 years (Kraus & Carter, 2018).

There remains a debate as to the ability of current benthic monitoring to detect adequately fine change in benthic community. This is because the relatively high cost to conduct benthic grab sampling and analysis makes large sample number surveys infinitely expensive, coupled with the high natural variability in benthic communities both spatially and temporally makes confidently identifying change challenging. Franco et al., 2015 reviewed multiple offshore windfarm surveys and aimed to assess the minimum detectable effect size (MDES) of change in Species richness, abundance and biomass. They concluded that under the average number of stations (four stations, three replicates per area) the MDES for mean species abundance was 50% i.e., there had to be a 50% change (increase/decrease) in species richness to be identified using standard parametric statistical methods. Furthermore, they calculated that to identify a 10% change in species richness would require a minimum of 10-15 stations (3 replicates) per area. 10% change being a suggested change threshold at which mitigations should be required (Rogers Et al 2008). Thus, there is debate as to if current offshore windfarms has sufficient sampling power to confidently identify community change.

1.7 Marine Data Exchange and CEFAS Baseline Dataset

The Marine Data Exchange is an online database created by The Crown Estate in 2013 to provide data and reports associated with Crown Estate assets and licenses within the marine environment. There is (as of 2022) 200 TB of survey data associated primarily with offshore wind projects, but also aggregates, wave, tidal stream and other research data. The CEFAS Regional Seabed Monitoring Programme (RSMP) dataset comprises 33,198 samples from 777 grab surveys, collected from a combination of industry, government and academic based projects (Cooper and Barry, 2017). These data sources allow academic study of the benthic environment by removing the monetary and time barriers to collecting and processing large numbers of samples, making large scale benthic assessments possible.

1.8 Water Framework Directive (WFD), UKTAG and the Marine Strategy Framework Directive (MSFD)

The Water framework Directive (WFD) is EU legislation that aims to improve and maintain the quality of the water systems (including lakes, rivers, canals, transitional and coastal waterbodies) of its member states, including the UK. The UK Technical Advice Group (UKTAG) works within the WFD legislation and aims to set environmental standards by which to assess water quality (UKTAG, 2008). Within each waterbody a number of elements (water chemistry, plankton blooms, angiosperm monitoring, heavy metals, benthic assemblage etc) are monitored, assessed and classified based on whether the element meets specific environmental and ecological standards. Where a waterbody has not met the set environmental standards, an investigation and Reasons for Not Achieving Good ecological status (RNAGs) are identified (Collins et al., 2012).

The Marine Strategy Framework Directive (MSFD), aims for all marine European regions and subregions to meet “Good Environmental Status” in 11 descriptors including Marine pollution, seabed integrity, biodiversity and food web dynamics (Long, 2011). The benthic descriptor has targets regarding I) habitat distribution, II)habitat extent, III) habitat condition, physical damage and the condition of the benthic community. The two regions which fall within UK waters are the Celtic Seas and the Greater North Sea.

1.9 The Infaunal Quality Index (IQI)

The Infaunal Quality Index (hereafter IQI) (Equation 1) is a multimeric index used for assessing the health of benthic invertebrate assemblages within coastal and transitional waterbodies. It is currently used by UK agencies amongst other EU member states fulfilling the requirements of Article 8; Section 1.3 of Annex II and Annex V of the Water Framework Directive (UKTAG, 2014a). The IQI compares three ecological metrics (AMBI, Simpsons Diversity Index and Species Richness) from a benthic sample with theoretical undisturbed or minimally disturbed reference assemblage metrics based on the sample's salinity and sediment statistics (Phillips et al., 2014). The IQI is sensitive (i.e., able to detect slight change) to nutrient enrichment, chemical pollutants and physical disturbance (i.e., smothering) (Phillips et al., 2014). The waterbody IQI classifications are used within the MSFD. The IQI assessment splits regions into 10km^2 areas, and assesses the number of “Good” and “Not Good” classifications, with an acceptable level being 85% of the area at Good status. This assessment also uses data for offshore oil and gas surveys, and aggregates disposal sites (UKMMAS, 2018 [Accessed 04:2023]).

Equation 1 The IQI equation.

$$EQR = \left(\left(0.38X\left(\frac{1-\left(\frac{AMBI}{7}\right)}{1-\left(\frac{AMBI_{Ref}}{7}\right)}\right)\right) + \left(0.08x\frac{1-\lambda'}{1-\lambda'_{Ref}}\right)\right) + (0.54\left((\frac{S}{S_{Ref}})^{0.1}\right) - 0.4)/0.6$$

AMBI refers to the AMBI value calculated in section x
λ' refers to Simpsons Diversity Index
S refers to Species/taxa richness
X_{Ref} refers to the metric reference condition

1.10 Water Framework Directive, Marine Strategy Directive Framework and Windfarms

A total of 18 coastal and 4 transitional WFD and waterbodies around England and Wales respectively contain areas with active windfarm cables and windfarm areas. Including Burbo Bank and Gunfleet offshore wind farms which are both totally within a coastal waterbody (Mersey Mouth and Essex coastal waterbody respectively) (EMODnet, 2022; Environment Agency, 2021; Natural Resources Wales, 2022). Under WFD protocols an IQI assessment is required to satisfy the infaunal element of WFD monitoring within all transitional and coastal waterbodies, including those containing windfarm infrastructure. To date little to no investigations have been undertaken to assess how adequate an IQI waterbody assessment is for assessing waterbodies with windfarm construction present. As a key impact from windfarm construction is a change in sediment characteristics and hydrodynamic regime (Coolen et al., 2022; Page et al., 2019) which is accounted for within the IQI process (Phillips et al., 2014) and in a sense negated during the calculations. Additionally, many of the significant impacts of windfarm construction have been noted as being acute in nature, there is therefore doubt whether a WFD waterbody analysis will detect these acute changes or if these changes will be masked by the wider waterbody sampling. (UKMMAS, 2018 [Accessed 04:2023]) outlines a lack of offshore data used in MSDF IQI analysis, the question is thus raised if offshore windfarm data could be used for this analysis in addition to oil and gas and aggregates.

1.11 Aims

This study will use benthic macrofaunal monitoring data and Particle Size Analysis (PSA) from benthic grab samples, collected during the pre-construction and 1 year post-construction benthic monitoring surveys of four offshore windfarm developments within UK waters, publicly available from The Marine Data Exchange. The aim is to assess if an IQI based waterbody analysis will detect change in benthic quality, by comparing the IQI protocol against standard multivariate assemblage analysis.

The specific aims of this study are to:

- Carry out waterbody IQI analysis of key areas of windfarm projects.
- Compare the IQI outcomes between pre-construction and 1 year post- construction with the aim of identifying change.
    - Hypothesis 1: the IQI will decrease at a waterbody level between Pre-Construction and Post-Construction.
    - Hypothesis 2: the submetrics (AMBI, Simpsons Diversity Index and species richness) will decrease at a waterbody level between Pre-Construction and Post-Construction.
- Carry out multivariate community analysis of the same areas.
    - Hypothesis 3: the benthic infaunal assemblage will change at a waterbody level between Pre-construction and Post-construction.
    - Hypothesis 4: the benthic infaunal assemblage diversity will change at a waterbody level between pre and post construction.

- Compare the outcomes of IQI analysis and community analysis.
- Assess if the construction of an offshore windfarm will alter the sediment profile of the surrounding broad scale area.
    - Hypothesis 5: mean grain size and sorting will change at a waterbody level between Pre-Construction and Post-Construction.
    - Hypothesis 6: mean grain size and grain sorting influences the species richness of an area.
    - Hypothesis 7: mean grain size and grain sorting influences the benthic community of an area.

2.0 Methods

2.1 Data Source and Data Requirements

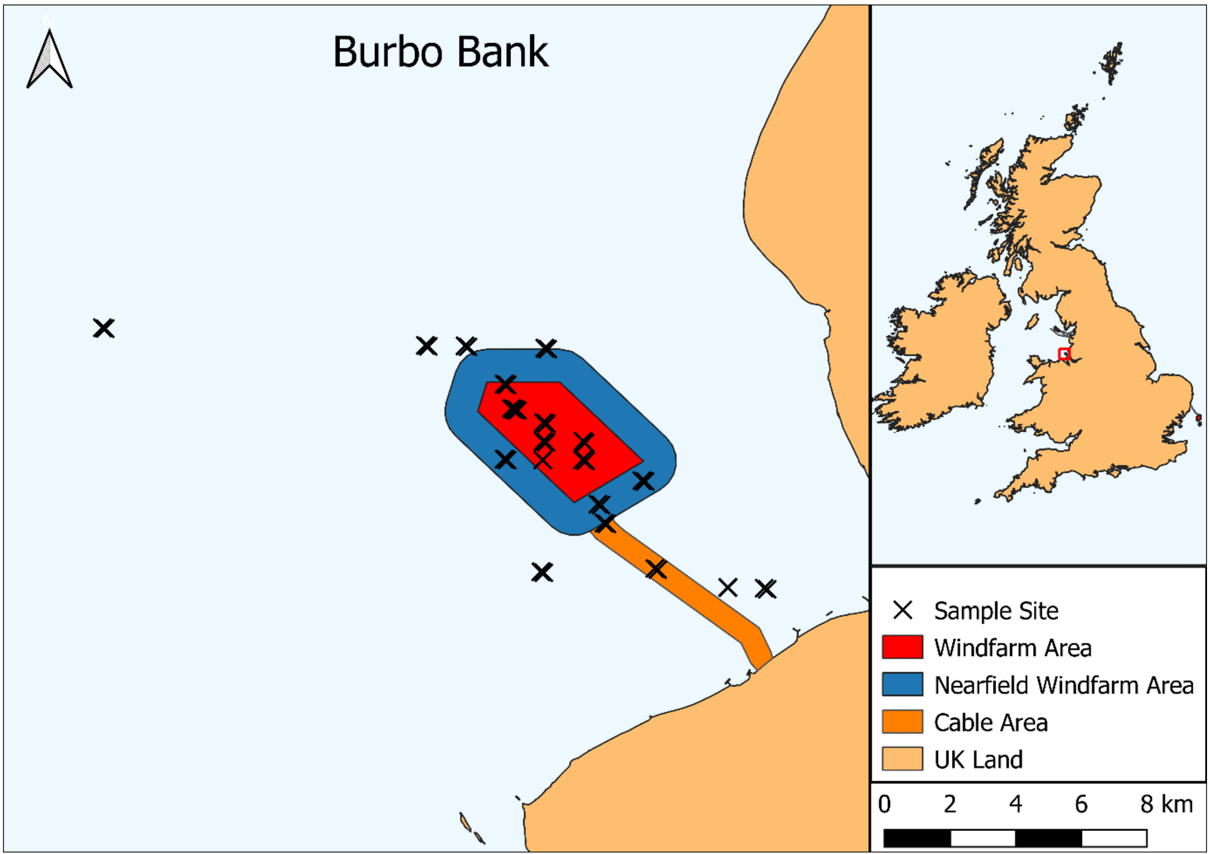
Wind farm summary data was downloaded from the European marine observation and data network (EMODnet, 2022) and filtered for only active windfarms (as of 2021). Each individual windfarm was then searched for on the Marine Data Exchange (The Crown Estate, 2022)and all wind farm projects which contained benthic survey data from pre-construction and some period post constructions were downloaded. Additional searches were made within the CEFAS RSMP baseline dataset for similar data. All data had to conform to standard benthic protocols, i.e.: the lab must have been part of the NMBAQC data quality assurance scheme to ensure standard taxonomic accuracy; sediment must have associated particle size analysis (PSA); samples must have been collected with grabs with an area of 0.1 m^2 and sieved over a 1 mm mesh. In total 6 windfarms had data acceptable for this study: Burbo Bank, Gunfleet, Greater Gabbard, Walney, Thanet and Robin Rigg. Though the post construction surveys were not consistent within Thanet and Robin Rigg, which only had data available for 2 ,3 and 4 years post construction, Therefore, Thanet and Robin Rigg data were removed and only windfarms which had data for pre-construction and one year post construction were selected (Table 1). While the inclusion of surveys taken 2,3 and 4 years post construction would have been beneficial to assess succession and timeframes of equilibrium, it was considered beyond the scope of this investigation which aimed to assess how relatively short term disturbance may impact the benthic community and health.

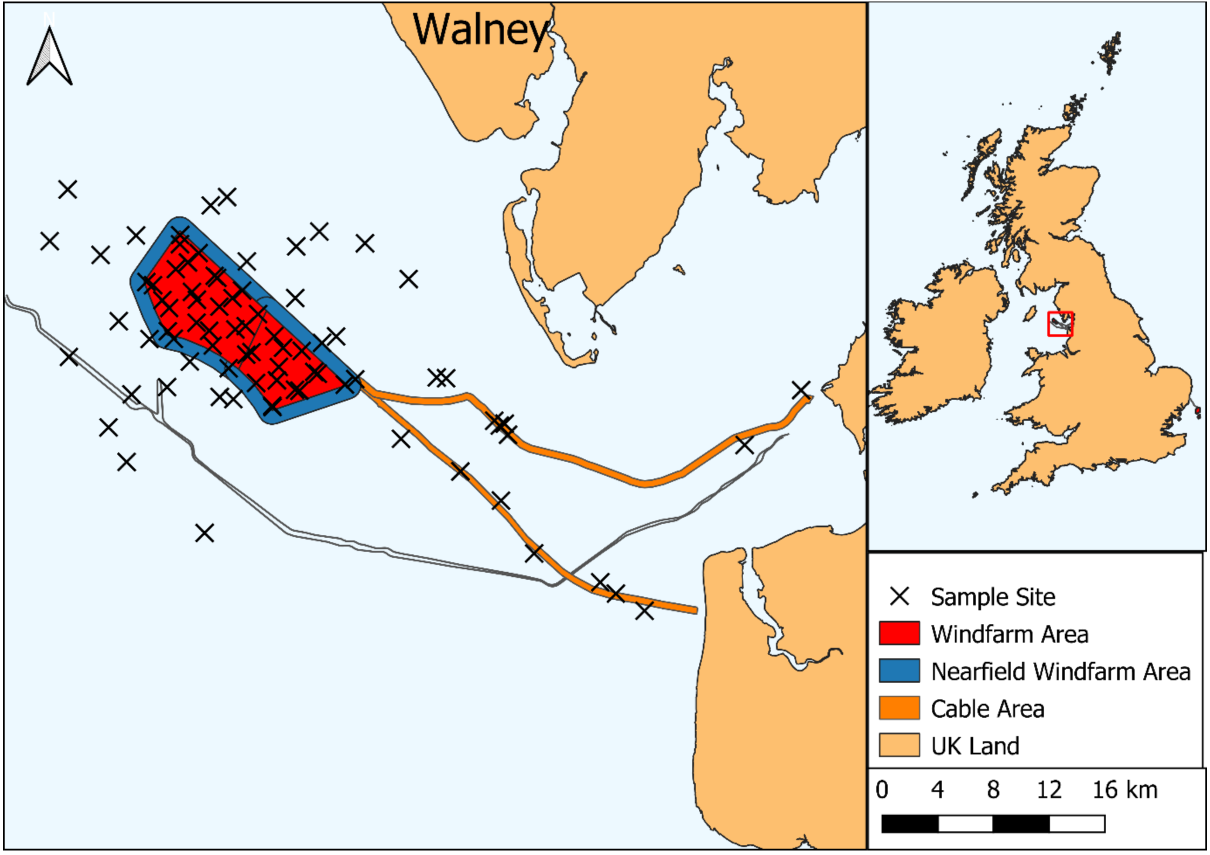
2.1.1 Sites

Four windfarms were selected for this study, these were Burbo Bank, Walney, Greater Gabbard and Gunfleet. Burbo Bank and Walney are located within the Irish sea, while Greater Gabbard and Gunfleet are located in close proximity to each other near the Thames (Figure 1).

Table 1 A summary of windfarm construction information for the Burbo Bank, Walney, Greater Gabbard and Gunfleet offshore windfarm developments.

Windfarm	**Date of pre-construction survey**	**Date of 1 year post construction survey**	**Pre-construction Survey and analysis carried out by**	**Post construction survey and analysis carried out by**	**date of windfarm construction**	**Nearest WFD waterbody**	**Number of wind turbines**	**Type of turbine structure**	**Area of windfarm (m**
Burbo Bank	Sep 2005 - Oct 2005	Sep 2007	(CMACS, 2006)	(CMACS, 2007)	May-August 2006 – monopile installation, May 2007 array cable laying	Within Mersey Mouth	25	Monopile	22,500
Walney	Apr 2005 - May 2005	Dec 2012 - Jan 2012	(CMACS, 2009)	(CMACS, 2012)	Jun 2012	Cumbria	51	Monopile	88,600
Greater Gabbard	Nov 2004 - Jun 2005	May2013	(CMACS, 2005)	(CMACS, 2014)	Sep2012	Within Essex	140	Monopile	167,700
Gunfleet	May-07	May2010	(RPS, 2008)	(CMACS, 2010)	May2010	Essex	48	Monopile	86,000


Burbo Bank
Sample Site
Windfarm Area
Nearfield Windfarm Area
Cable Area
UK Land
0 2 4 6 8 km


Walney
Sample Site
Windfarm Area
Nearfield Windfarm Area
Cable Area
UK Land
0 4 8 12 16 km

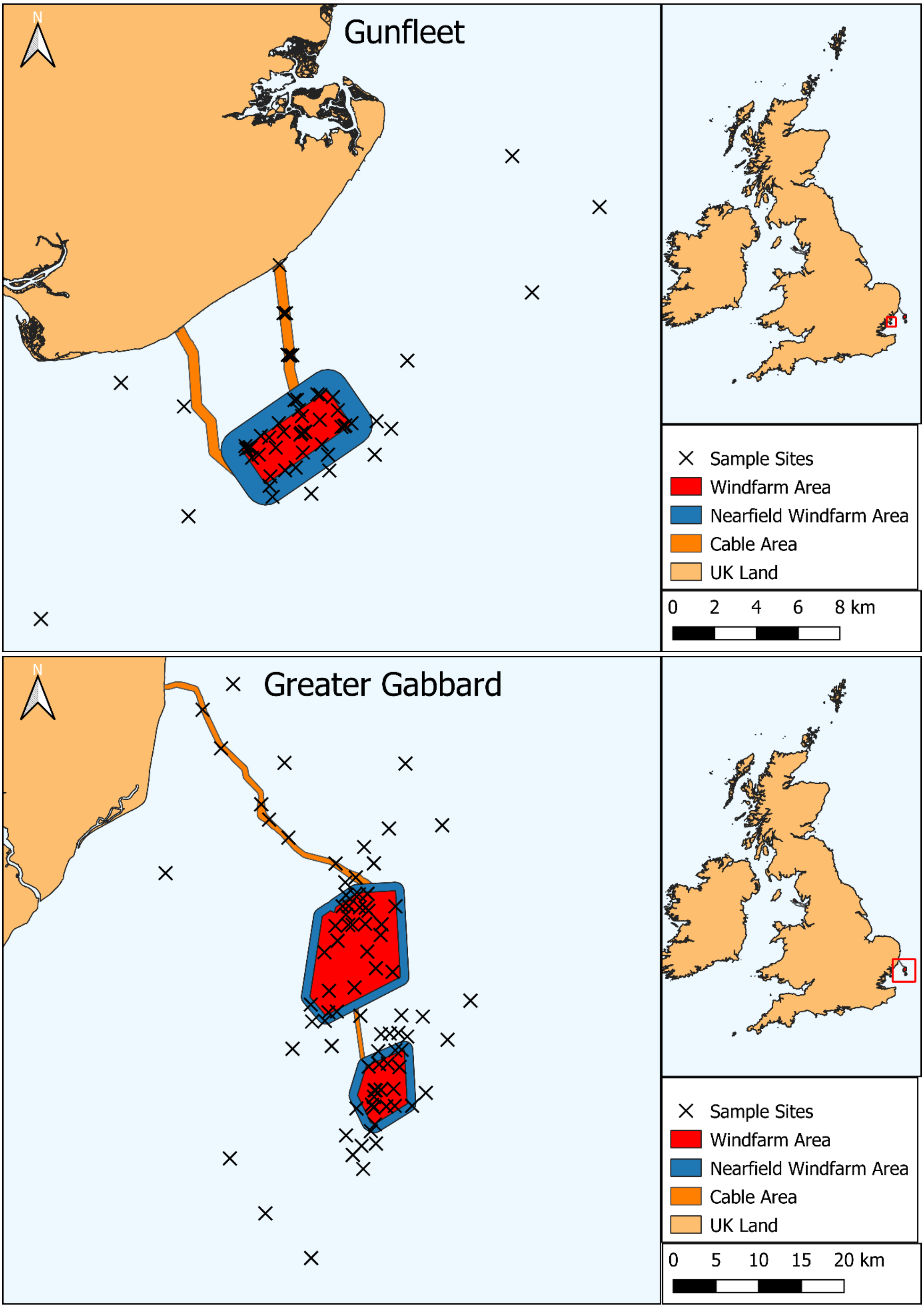


Figure 1 Maps of the benthic grab sample sites within Burbo Bank, Walney, Gunfleet and Greater Gabbard offshore windfarms, in addition to the windfarm, nearfield and cable areas used to assign sample types to data. Insets show the locations of the windfarms around the United Kingdom. Maps were made using Q GIS V.3.10, using sample position data included in the Metadata from https://www.marinedataexchange.co.uk/[Accessed 17/10/2022] and windfarm polygon layers available from https://www.emodnet-humanactivities.eu/ [Accessed 17/10/2022].

2.2 Data Manipulation and Processing

2.2.1 Abundance Data Truncation and Manipulation

Once adequate datasets were selected, data were extracted either from Microsoft Excel spreadsheets or from monitoring report appendices. Data were merged into one spreadsheet and the taxa list processed via the WORMS taxa match tool (WoRMS Editorial Board, 2022) to ensure all taxa names were up to date and identify any taxa synonyms, which were then merged. Additionally, all encrusting or colonial taxa were converted to presence/ absence data (1 /0) and any non-invertebrate taxa (fish, seaweeds etc) removed.

2.2.2 Particle Size Analysis (PSA) Data

PSA data were compiled into a single matrix and processed using the GRADISTAT Excel macro program, which produced sediment statistics and a ‘Folk Description’ based on the Folk Triangle (Figure 2).

2.3 Sediment Data

2.3.1 Folk Triangle

The Folk Triangle is a method of classifying sediment based on the proportion of gravel, sand and clay which provide qualitative descriptions of the sediment i.e., muddy gravel (mG) or gravelly muddy sand (gmS) (Figure 2). this method was used to describe the sediment within the IQI tool.

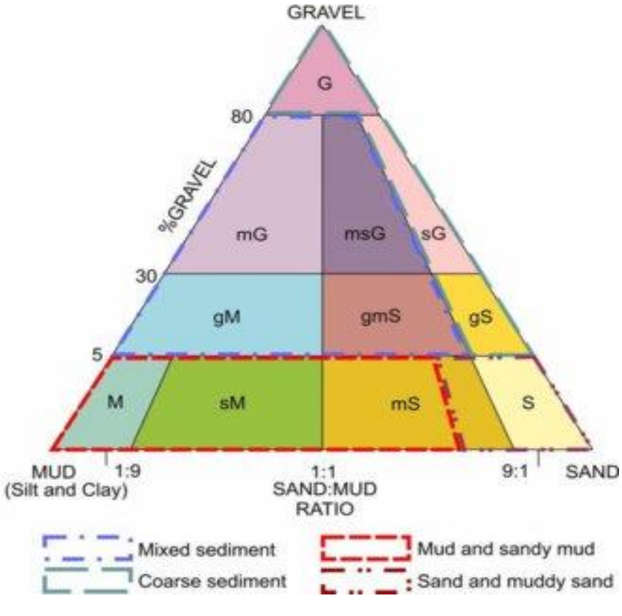


Figure 2 An example of the Folk Triangle, where a triangle is divided based on the ratio of mud, sand and gravel. Capitalised letters within the triangle represent the dominant fraction. taken from (Evans and Aish, 2016)

2.3.2 Mean Grain size and Grain sorting

Both mean grain size and grain sorting were derived by using sample cumulative frequency curves. As seen in Equation 3, mean grain size (M_Z) is calculated by identifying the grain size (Φ) at the 16th, 50th and 84th percentile of a cumulative frequency curve. Grain sorting describes how uniform the sediment grains are within a sample. A low sorting value indicates that sediment grains are of a similar size, while a high sorting value indicates a greater distribution of grain sizes. as seen in equation 2, grain sorting (σ_I) is calculated by identifying the grain size (Φ_x) at the cumulative 16th,84th, 95th and 5th percentile. As seen in Table 3 a very well sorted sample has a sorting value of < 0.35 while an extremely poorly sorted sample has a sorting value of >4.00. these equations are based on the 1957 Folk and Ward Logarithmic (using Phi units) method and are taken from (Blott and Pye, 2001). Phi is expressed in
Equation *2*.

Equation 2 The Phi (Φ) Equation

$$\Phi = -Log_2(Grain\ size\ (mm))$$

Equation 3 The 1957 Folk and ward logarithmic (using Phi units) mean grain size (M_Z) calculation, where Φ_x is the grain size at the cumulative percentile *x*

$$M_Z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$$

Equation 4 The 1957 Folk and Ward logarithmic (using Phi units) grain sorting (σ_I) calculation where Φ_x is the grain size at the cumulative percentile x

$$\sigma_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$$

Table 2 The corresponding Phi scale values and sediment grain diameter (µm)

Phi	Grain Diameter (um)
-11	2048000
-10	1024000
-9	512000
-8	256000
-7	128000
-6	64000
-5	32000

Phi	Grain Diameter (um)
-4	16000
-3	8000
-2	4000
-1	2000
0	1000
1	500
2	250
3	125
4	63
5	31
6	16
7	8
8	4
9	2

Table 3 A description of grain sorting based on the 1957 Folk and Ward logarithmic method

Sorting (σ_I)	
Very Well Sorted	< 0.35
Well Sorted	0.35-0.50
Moderately Well Sorted	0.50-0.70
Moderately Sorted	0.70-1.00
Poorly Sorted	1.00-2.00
Very Poorly Sorted	2.00-4.00
Extremely Poorly Sorted	>4.00

2.4 Spatial Data Processing

Coordinates for each grab sample were extracted from the data and converted to a standard Coordinate reference system (British National Grid (BNG)). Shapefiles containing polygon layers for windfarm areas and export cable areas were downloaded via The Marine Data Exchange, layers were filtered for only the 4 stated windfarms and associated export cables. A Nearfield buffer of 1000 m was created around each windfarm using the ‘Buffer’ tool within QGIS V3.10.10. though this distance may be liberal, it ensures many medium scale hydrodynamic effects are included within the Nearfield site, in addition to encompassing the areas with lower fishing effort (including a legal safety zone of 500 m from assets under construction and a 500 m buffer to account for areas of reduced fisheries activity due to fear of fouling gear (FLOWW, 2014; Hooper et al., 2017). The “Join by location” tool was used within QGIS V3.10.10 to assign grab samples to one of 4 groups,

1. **Windfarm**: samples within the windfarm polygon, where impacts from monopile construction, change in hydrographic and sediment conditions is most likely to be detected;
2. **Nearfield windfarm**: samples within the 1000 m windfarm buffer zone where some indication of monopile construction may be detected due to increased turbidity;
3. **Cable**: samples from within the cable corridor where impacts from cable laying is most likely to be detected, due to dredging activity and increase in EMF within the immediate cable area;
4. **Windfarm reference**: samples that were not in the previous three categories and were deemed to be least impacted by the windfarm infrastructure but contain similar benthic characteristics (control sites).

2.5 IQI and Metrics

2.5.1 AMBI

The AZTI Marine Biotic Index (AMBI) (Equation 5) groups taxa into 5 ecological groups (EG) based on their tolerance to disturbance. EGI taxa are the most susceptible to disturbance and are found in lowest abundance in highly disturbed samples. EGV taxa are considered first order opportunists and are most tolerant of disturbed environments, found in highest abundance in highly disturbed samples and are the least susceptible to disturbance, taxa in groups II-IV have increasing levels of tolerance to disturbance.

The AMBI is based on the concept that under ecologically stressed conditions due to sediment contamination and elevated nutrient loading, taxa sensitive to these stressors (AMBI EGI) will reduce in abundance while opportunistic taxa with high reproductive and development rates and which are disturbance tolerant (AMBI EGV) will increase in abundance, thus the AMBI is a ratio between the proportion of disturbance sensitive and tolerant taxa within a sample (Equation 5) (Borja and Muxika, 2005).

Equation 5 The AMBI calculation where %EG I-V refers to the percentage of the sample fauna within AMBI group I-V

$$\mathrm{AMBI} = \{(0\mathrm{x}\%\mathrm{EG\ I}) + (1.5\mathrm{x}\%\mathrm{EG\ II}) + (3\mathrm{x}\%\mathrm{EG\ III}) + (4.5\mathrm{x}\%\mathrm{EG\ IV}) + (6\mathrm{x}\%\mathrm{EG\ V})\}/100$$

2.5.2 Simpsons Diversity Index

Simpsons Diversity Index (Equation 6) is a metric for how even the spread of taxa is within the sample. The Simpsons Diversity Index is between 0 and 1, a sample with a low index value will generally be dominated by a small number of taxa, while a sample with a high index value will have a greater number of taxa contributing significantly and evenly to the assemblage.

Equation 6 The Simpsons Diversity Index where n is the abundance of individuals of a taxon. And N is the abundance of all individuals of all taxa

$$D = 1 - \left(\frac{\sum n(n-1)}{N(N-1)}\right)$$

2.5.3 Species Richness

Species Richness is simply the number of different Taxa found within a sample and is a metric for diversity.

2.5.4 Infaunal Quality Index (IQI)

The Infaunal Quality Index (IQI) (Equation 1) consists of three metrics, AMBI, Simpsons Diversity Index and Species Richness. The output from an IQI analysis is an Ecological Quality Ratio (EQR) and is derived from comparing each metric with a “Reference” metric, which is a regression derived metric value based on the sample’s sediment statistics and salinity.

2.5.5 Reference Conditions

In order to assess the health of a benthic sample the IQI model compares each metric to a theoretical undisturbed reference metric, which was calculated using pressure gradient analysis from nutrient and contaminant disposal sites using two data sets during the development of the tool and has since been updated with further data sets to improve the reference model (Phillips et al., 2014). Note this reference metric is independed of reference sites included in this study. In order to compensate for non-disturbance-based bias i.e., habitat and sampling protocol, a range of reference conditions have been gathered, based on current data, expert knowledge and statistical models. Different reference condition values are available based on a sample's sediment type and sample salinity, along with the sampling protocol (subtidal grab/intertidal core, sieve mesh size and volume of sediment collected).

2.5.6 Ecological Quality Ratio (EQR)

The output of the IQI protocol is an Ecological Quality Ratio (EQR) with a range of 0-1. The EQR is for an individual sample and can be averaged across varying spatial scales to give an average water body EQR score. The boundaries for the EQR used within the Water Framework Directive are found in Table 4.

Table 4 Summary of the Water Framework Directive (WFD) Ecological Status Ecological Quality Ratio (EQR) ranges

Ecological Status	EQR range
High	0.75-1
Good	0.64-0.75
Moderate	0.44-0.64
Poor	0.24-0.44
Bad	0-0.24

2.5.7 IQI Workbook

The IQI workbook (UKTAG, 2014b) currently available (last updated 2014) was used. A complete species matrix consisting of taxa names as row names and sample code as column names with taxa abundances populating the cells were inputted into the IQI Excel macro. Due to the outdated taxa list within the IQI workbook, taxa had to be compared with the taxa list within the excel macro and updated taxa renamed to match 2014 taxonomy to allow the macro tool to calculate the AMBI Score. Within the macro the species data were truncated by removing non-invertebrate and non-benthic taxa such as plankton and fish species. Colonial and encrusting species values were converted to either present (1) or absent (0), and an AMBI group assigned based on the AMBI referenced list within the macro, following which the macro calculated each sample’s AMBI, Simpsons Diversity Index and Species Richness. In order to calculate the IQI, the sample’s Folk description extracted from the GRADISTAT program were inputted. In addition to the area’s salinity regime (Coastal (32.5 ppt)) which best described the salinity category of the windfarm within the IQI tool options, in addition to elements of the survey method (i.e., grab sample and 1 mm mesh size) were inputted into the Excel macro in order to calculate the reference value for each metric for each sample. Only sample EQR, AMBI, Simpsons Diversity index and species richness were extracted from the tool for further analysis.

2.6 Statistics

2.6.1 sample classification

To run the suite of statistics required for this study, samples were grouped within multiple spatial and temporal scales outlined in Table 5

Table 5 A description of sample grouping terms used within this document.

Sample Group	Description
Windfarm	“Windfarm” refers to the windfarm the data was collected, either Burbo Bank, Walney, Gunfleet or Greater Gabbard
Site Type	“Site type” refers to the group assigned in section 2.5
Phase	Phase refers to the sampling phase the samples were taken from, either Pre-Construction or Post-Construction

2.6.2 Univariate Analysis

In order to assess the change in univariate parameters pre and post construction (Hypothesis 1,3 and 5), a suite of non-parametric analyses was carried out, this was because EQR, AMBI and Simpsons Diversity Index are ratios and thus bounded between 0-1. When the data were transformed using an arcsine transformation and tested for normality, all data were found to not meet the assumptions required for parametric testing. For two level testing the Wilcoxon signed rank test was used. For multiple factor testing the Kruskal-Wallis test was used, with a Dunn’s Post-hoc test with a Bonferroni correction to identify significant pairs. Generalised linear regression modelling analysis was carried out on species richness, mean sediment grain size and sorting and data assuming a Poisson distribution family (Hypothesis 6). All univariate statistics were carried out using the statistical program R V.1.3.959 (R Core Team, 2015).

2.6.3 Multivariate Analysis

Multivariate analysis was carried out within the Primer V.7 & PERMANOVA statistical package (Clarke K and Gorley R, 2015). Once the species abundance matrix was inputted, the data was fourth root transformed after examining shade plots of the raw and square root transformed data. The fourth root transformation down-weights extremely abundant species while upweighting rarer species allowing a more comprehensive analysis of the assemblage. This was done to reduce the influence of high density aggregations of certain taxa not present in the remaining waterbody and lower the impact of seasonally high abundances of juvenile taxa between pre and post construction. It is acknowlaged that this transformation may have lowered the sensitivity of the analysis to change lowering the influence of high density opportunistic taxa potentially increasing the risk of type II errors, though this transformation will produce a more comparable waterbody assessment less sensitive to single sample influence. Following this, a resemblance matrix was created based on samples' Bray-Curtis dissimilarity index.

The change in community (Hypothesis 3) was assessed using the PERMANOVA routine using a fully nested (Windfarm (Site type (Phase))) design, and where a main test was found to be significant, a post-hoc pairwise comparison was carried out. Monte Carlo tests were included in the pairwise analysis in order to significantly test groups with insufficient permutation capability. The groups heterogeneity (Hypothesis 4) was assessed using the PermDisp routine, again using a fully nested design.

A SIMPER analysis was conducted to identify what taxa contributed greatest to the community change between Pre-Construction and Post-Construction (Hypothesis 3 and 4) with the abundance change (true abundance and 4th root transformed abundance) calculated.

Sediment data (mean grain size (phi) and grain sorting (phi)) was inputted into a separate sheet and normalised by subtracting the mean and dividing by the standard deviation, for each variable (Clarke et al., 2014). A RELATE routine followed by a DistLm routine was carried out to assess how the sediment characteristics impacted the benthic assemblage (Hypothesis 7).

2.6.4 Multiple Testing and Bonferroni Adjustments

In order to carry out pairwise nested comparisons between pre and post construction, multiple tests were conducted between pre and post construction at each site type at each windfarm (16 tests in total per nested analysis) for various univariate and multivariate parameters. To account for the elevated risk of type 1 errors, a Bonferroni adjustment was made to the Alpha value. This was calculated to be α = 0.003. (0.05/16 (α/the number of tests run)). While tests were available (Dunn's test) which takes multiple testing adjustments into consideration, the process required to carry out these tests would have increased the theoretical number of tests to 108 thus applying a much more conservative Bonferroni adjustment and likely leading to a greater risk of type II errors. Additionally, the PRIMER 7 and PERMANOVA software do not apply alpha corrections, thus to aid in clarity hereafter the alpha value will be 0.003 for nested analyses, and 0.05 for non-nested analyses or where a Dunn's test has been used.

3.0 Results

3.1 Summary

A total of 669 samples were taken from 272 sampling stations.; 273 benthic grab samples were included in the pre-construction dataset and 396 benthic grab samples in the post-construction dataset. These were taken from 135 and 137 sample stations respectively (Table 6). To avoid issues associated with pseudoreplication, grab samples (technical replicates) were mean averaged for each station level before commencement of analysis (Table 6). This was done after univariate variates were calculated, but before the multivariate analysis was undertaken. It was done to reduce the weighting of stations which had multiple replicates taken one survey and single replicates taken another.

A total of 771 taxa were included in this analysis. These taxa were grouped within 447 genera and 260 families within 18 phyla. The phylum Annelida contributed 293 taxa to the analysis, the phylum Echinodermata contributed 28 taxa, the phylum Mollusca contributed 124 taxa, and the phylum Arthropoda 189 taxa. 570 taxa were identified to species level, 117 to genus level, 48 to family level, 12 to order level, 10 to class level and 7 to phyla level.

3.1.1 Benthic Communities

A SIMPER analysis was carried out within each windfarm with a 25% maximum cumulative contribution percentage, to assess what taxa contributed most to each assemblage based on 4th root transformed data. Burbo Bank's highest contributing taxa were the Polychaetes *Lagis koreni, Spiophanes bombyx* and *Magelona johnstoni* (contribution = 8.58 %, 6.77 % and 5.89 % respectively) and the bivalve *Kurtiella bidentata (*Contribution = 7.98%). Gunfleet was dominated by the Polychaete *Nephtys cirrosa* (contribution = 18.89%) and the bivalve *Nucula nitidosa* (contribution = 13.22%). Greater Gabbard had the largest number of taxa contributing 25% to the assemblage: Nemertea contributed 7.19%, the polychaetes *Glycera lapidum* and *Ophelia borealis* contributed 5.23% and 4.96% respectively and the bryzoan *Aspidelectra melolontha* contributed 4.70%. Walney was dominated by *Phoronis* spp (6.50%), *Nephtys incisa* (6.64%) and *Nucula nitidosa* (4.68%).

3.2 Overall Change in Benthic Community

The change in benthic quality and benthic community assemblage was compared pre and post construction. There was no significant change in the ecological quality ratio (EQR) between pre and post construction (Wilcoxon signed rank test, W = 8896, p-value = 0.5884; Figure 3). The median EQR fell from 0.695 during the pre-construction surveys to 0.693 during the post construction surveys.

A significant difference in group centroid location based on a Bray-Curtis Dissimilarity matrix was apparent when a PERMANOVA was carried out on the the 4th root transformed species matrix (Pseudo-F = 8.727, P(Perm) = 0.001, Unique Permutations = 999).

Table 6 A summary of the number of stations included within each site type, phase and windfarm. The numbers in brackets indicate the number of benthic grab samples (technical replicates) included within each group.

	Burbo Bank	**Greater Gabbard**	**Gunfleet**	**Walney**	**Total**
Windfarm	**17 (49)**	**53 (101)**	**35 (64)**	**42 (126)**	**147 (340)**
Pre-Construction	9 (24)	33 (43)	20 (20)	25 (75)	87 (165)
Post-Construction	8 (22)	20 (58)	15 (44)	17 (51)	60 (175)
Nearfield Windfarm	**4 (12)**	**22 (46)**	**6 (14)**	**14 42)**	**46 (114)**
Pre-Construction	2 (6)	11 (13)	2 (2)	6 (18)	21 (39)
Post-Construction	2 (6)	11 (33)	4 (12)	8 (24)	25 (75)
Reference	**16 (46)**	**13 (37)**	**6 (16)**	**10 (30)**	**45 (129)**
Pre-Construction	8 (24)	1 (1)	1 (1)	7 (21)	17 (47)
Post-Construction	8 (22)	12 (36)	5 (15)	3 (9)	28 (82)
Cable	**2 (6)**	**9 (21)**	**9 (17)**	**14 (42)**	**34 (86)**
Pre-Construction	1(3)	3 (3)	4 (4)	4 (12)	12 (22)
Post-Construction	1 (3)	6 (18)	5 (13)	10 (30)	22 (64)
Total	**39 (113)**	**97 (205)**	**56 (111)**	**80 (240)**	**272 (669)**

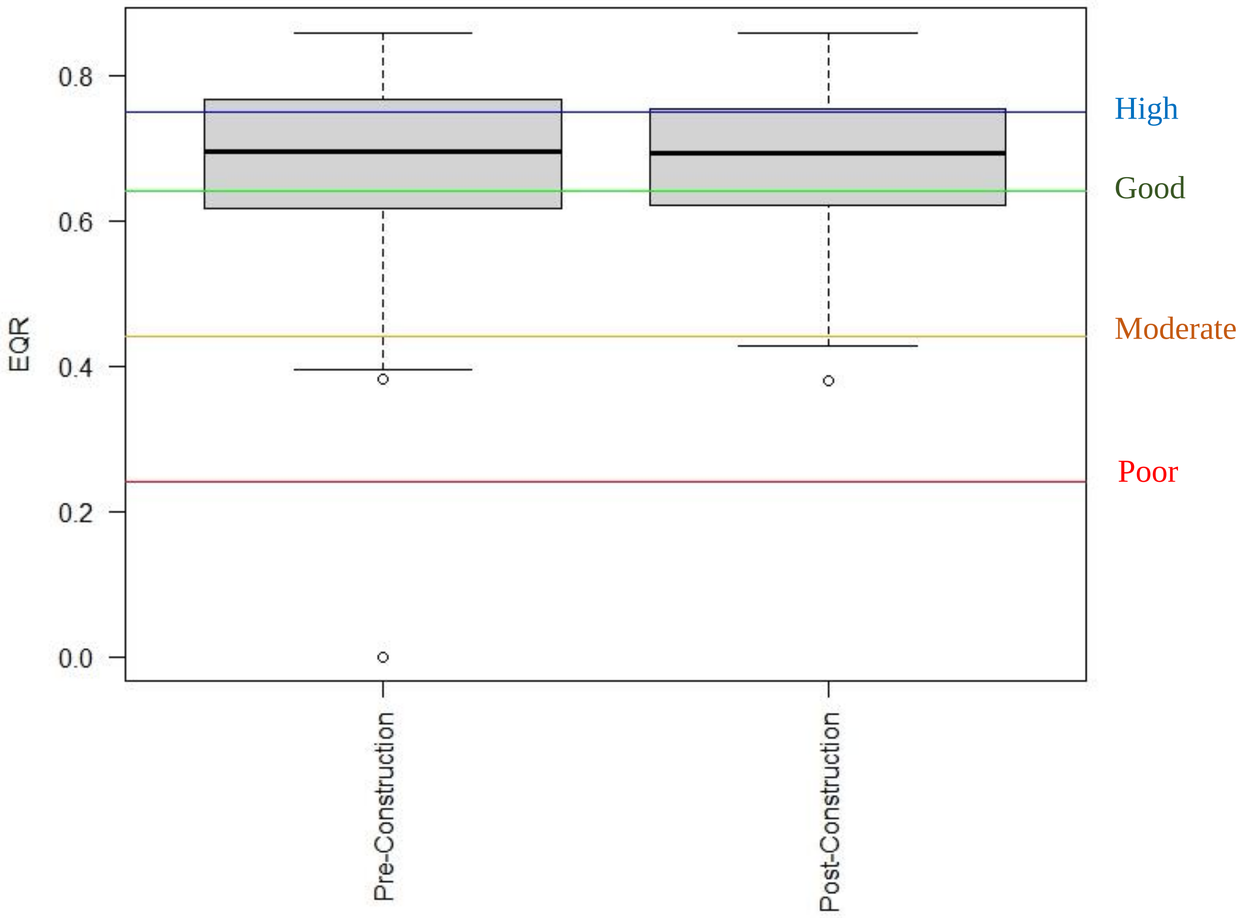


Figure 3 A boxplot showing the difference in Ecological Quality Ratio (EQR) of benthic communities surveyed pre-wind-farm construction and 1 year post construction using pooled data from 4 offshore windfarm developments (Burbo Bank, Walney, Gunfleet and Greater Gabbard). Coloured bands indicate the Ecological status boundaries. A Boxplot represents the spread of data within a distinct category, the bold line indicates the median value, the box represents the upper and lower quartiles, the outside lines represent the minimum and maximum values without outliers (defined as a data point that is outside 1.5 times the interquartile range above the upper quartile and bellow the lower quartile).

3.3 Inter-Windfarm Differences in Benthic Community

The difference in benthic community quality and assemblage between the four windfarms were assessed using only Pre-Construction data. There was a significant difference between windfarms (K-W Chi^2 = 46.596, df = 3, p-value < 0.001). A Dunn's Test with Bonferroni corrections was then carried out: Walney had significantly higher EQRs than Burbo Bank, Greater Gabbard and Gunfleet. While the other three windfarms were not significantly different from one another (Figure 4). The difference in benthic community assemblage was also assessed using a PERMANOVA with post hoc pairwise comparisons. It was found that there was a significant difference present between windfarms (Pseudo-F = 21.521, P(Perm) = 0.001, Unique Perms = 995) with all windfarms showing significant distinctness (Figure 5).

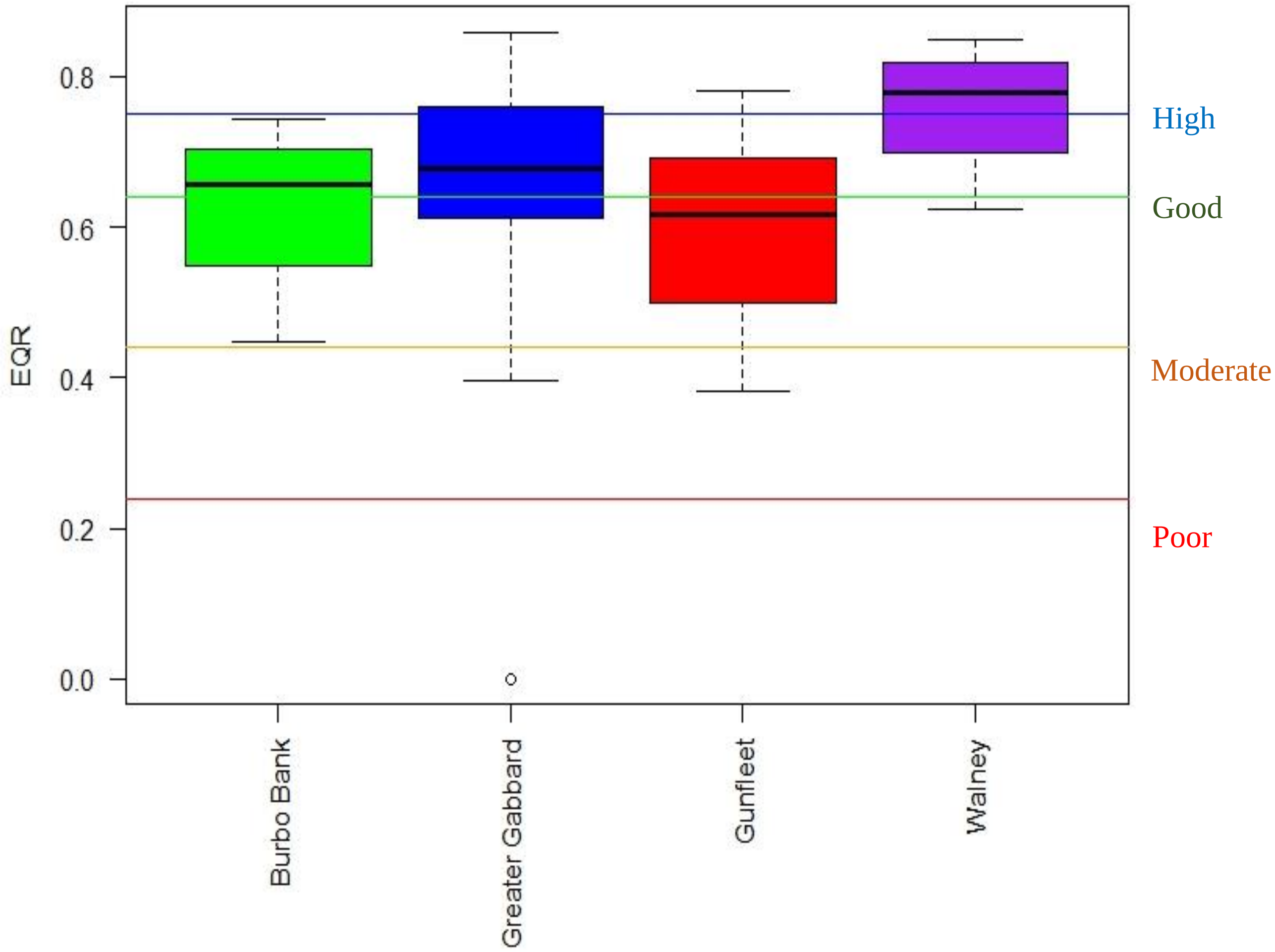


Figure 4 A boxplot showing the difference in Ecological Quality Ratio (EQR) of benthic communities surveyed pre-windfarm construction within 4 offshore windfarm developments (Burbo Bank, Walney, Gunfleet and Greater Gabbard). Coloured bands indicate the Ecological status boundaries A Boxplot represents the spread of data within a distinct category, the bold line indicates the median value, the box represents the upper and lower quartiles, the outside lines represent the minimum and maximum values without outliers (defined as a data point that is outside 1.5 times the inter-quartile range above the upper quartile and bellow the lower quartile).

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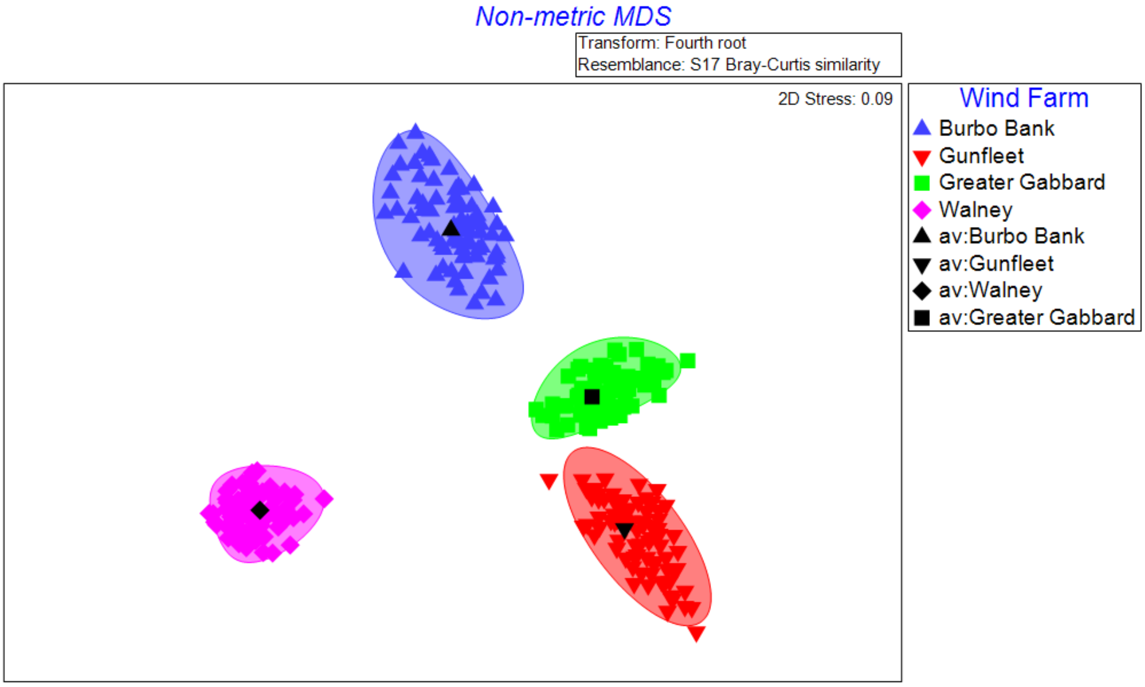

Figure 5 A 2-dimensional (2D) Non-Metric Multi-Dimensional Scaling (MDS) plots of bootstrapped averages of pre-construction sample stations within four windfarms within the UK, based on 4th root transformed data and a Bray-Curtis based resemblance matrix. A 2D MDS plot represent as Bray-Curtis Dissimilarity matrix in 2-dimensional space, with a data point's distance from all other data points representing its dissimilarity. Points closer together have a greater similarity. Black symbols represent the group centroids, while the coloured regions represent 95% confidence in sample grouping, note coloured points do not represent individual samples but bootstrapped averages

3.4 change in EQR and Benthic Community Between Pre and Post Construction

3.4.1 Change in EQR

When the median EQRs were compared between pre and post construction within each site type within each windfarm, no significant change was found in any sample type within Burbo Bank, Gunfleet, or Greater Gabbard. Within the Walney windfarm site type, the median EQR changed from 0.806 to 0.774, the Wilcoxon signed rank test statistic was calculated as W = 122, p-value = 0.02103. Under normal statistical conventions, this would indicate a significant change, however due to the analysis including multiple testing, a more conservative α value of 0.003 was used to determine significance. Thus, based on this analysis, it can be suggested that there was no significant change in IQI EQR between Pre and Post construction within any site types within any windfarms (Table 7, Figure 6). Thus the Null hypothesis (Hypothesis 1) can be accepted. If the area classifications are considered it can be seen that no windfarm area showed a change in classification, while this was apparent in other areas, this is likely due to the comparably low sampling effort in other areas confounding natural variation with true change.

Table 7 The outputs of pairwise Wilcoxon Signed rank non-parametric tests of Ecological Quality Ratio (EQR) difference between pre and post construction within 4 site types within 4 Offshore windfarm Developments. Significant differences are highlighted in bold. Note due to multiple testing α was set to 0.003 based on a Bonferroni adjustment. Coloured Mean EQR cells represent WFD classification, Red = Poor, Orange = Moderate, Green = Good, Blue = High.

Windfarm	Site	Phase	Mean EQR	Median EQR	W	P
Burbo Bank	Windfarm	Pre-Construction	0.615	0.651	27	0.413
		Post-Construction	0.557	0.551		
	Nearfield Windfarm	Pre-Construction	0.695	0.695	0	0.333
		Post-Construction	0.602	0.602		
	Reference	Pre-Construction	0.619	0.625	29	0.798
		Post-Construction	0.613	0.624		
	Cable	Pre-Construction	0.703	NA	NA	NA
		Post-Construction	0.652	NA		
Walney	Windfarm	Pre-Construction	0.801	0.806	122	0.021
		Post-Construction	0.774	0.774		
	Nearfield Windfarm	Pre-Construction	0.742	0.726	29.5	0.516
		Post-Construction	0.758	0.783		
	Reference	Pre-Construction	0.708	0.698	9	0.817
		Post-Construction	0.689	0.710		
	Cable	Pre-Construction	0.675	0.682	21	0.945
		Post-Construction	0.678	0.677		
Greater Gabbard	Windfarm	Pre-Construction	0.667	0.687	356	0.526
		Post-Construction	0.692	0.724		
	Nearfield Windfarm	Pre-Construction	0.646	0.740	50.5	0.532
		Post-Construction	0.647	0.681		
	Reference	Pre-Construction	0.395	NA	NA	NA
		Post-Construction	0.656	0.667		
	Cable	Pre-Construction	0.59	0.613	15	0.167
		Post-Construction	0.704	0.720		
Gunfleet	Windfarm	Pre-Construction	0.591	0.625	175.5	0.404
		Post-Construction	0.620	0.624		
	Nearfield Windfarm	Pre-Construction	0.686	0.686	4	1
		Post-Construction	0.682	0.676		
	Reference	Pre-Construction	0.534	NA	NA	NA
		Post-Construction	0.679	0.672		
	Cable	Pre-Construction	0.618	0.600	16	0.191
		Post-Construction	0.717	0.689		

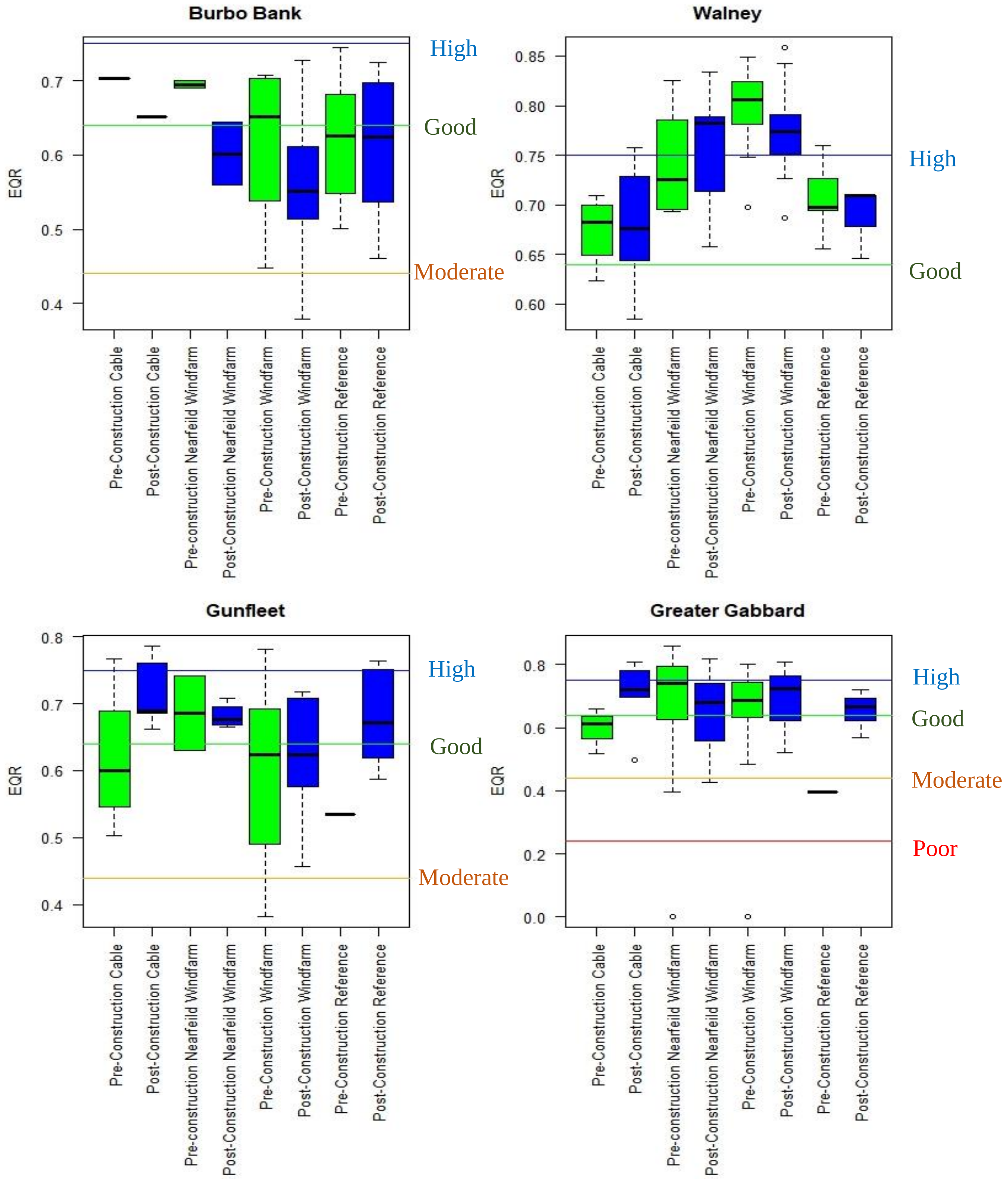

Figure 6 Boxplots showing the difference in Ecological Quality Ratio (EQR) of benthic communities surveyed pre-windfarm construction and 1 year post construction within 4 different site types within 4 offshore windfarm developments (Burbo Bank, Walney, Gunfleet and Greater Gabbard). Coloured bands indicate the Ecological Status boundaries. A Boxplot represents the spread of data within a distinct category, the bold line indicates the median value, the box represents the upper and lower quartiles, the outside lines represent the minimum and maximum values without outliers (defined as a data point that is outside 1.5 times the interquartile range above the upper quartile and bellow the lower quartile).

3.4.2 Community Composition Change at a Site Type Level

To assess if the benthic community assemblage changed between the pre and post construction surveys a fully nested PERMANOVA routine was carried out. The main test indicated that a significant difference in group centroids was present between at least two groups (pseudo f = 2.947, P(perm) = 0.001, unique permutations 997). A pairwise post-hoc PERMANOVA routine was carried out. Due to analysis including multiple testing an α value of 0.003 was used to assign significance. The permutational P value was used to determine significance when the number of unique permutations were above 400. Groups with a lower number of unique permutations used the Monty Carlo P value. this was done to allow significant p value thresholds to be met (p = 0.003) within groups where the number of permutations would otherwise inhibit a significant p value to be met (Table 8).

It was found that benthic community assemblages differed significantly between pre and post construction within all ‘windfarm’ site types as as identified though the difference in group centroid location of Pre-Construction and Post-Construction data groups (Table 8). Significant change in group centroid was also apparent for the ‘windfarm’, ‘nearfield windfarm’, and ‘cable’ site types of Walney, thus the Null hypothesis (Hypothesis 3) can be rejected. When Bootstrapped averages were examined, it can be noted that in all windfarms the amount of variance is much lower in the windfarm site types compared to the other site types, additionally it can be seen that in all windfarms there is difference between pre and post construction, however in many of the other areas, the variance is likely limiting the statistical power of the assessment. Conversely, the variance within the Walney groups were comparably low, this is possibly a reason why there was a significant difference between pre and post construction. Interestingly, within Greater Gabbard and Walney showed close centroids and groupings during the pre-construction survey, while in the post construction survey there is a clear separation. Under a null hypothesis it would be expected that the trajectories of all areas would be in a similar direction, and the group cluster would remain relatively intact, however a separation can be seen indicating a deviation of one group from another. This adds weight to the rejection of the null hypothesis (Figure 7).

Table 8 The output from nested pairwise PERMANOVA routines comparing pre and post windfarm construction, with four site types within 4 offshore windfarm developments. Outputs were based of 4th root transformed data within a Bray-Curtis resemblance matrix. Due to multiple testing α was set to 0.003 based on a Bonferroni adjustment. The P value derived from the Monte Carlo test was used when the number of unique permutations were below 400. Significant differences are highlighted in bold in a grey cell

Windfarm	Site	t	P(perm)	Unique Perms	P(MC)
Burbo Bank	**Windfarm**	**1.669**	**0.001**	**954**	**0.021**
	Nearfield Windfarm	0.869	0.662	3	0.551
	Reference	0.827	0.728	935	0.659
	Cable	NA	NA	NA	NA
Walney	**Windfarm**	**3.892**	**0.001**	**999**	**0.001**
	Nearfield Windfarm	**1.781**	**0.002**	**852**	**0.008**
	Reference	1.559	0.01	120	0.037
	Cable	**1.639**	**0.001**	**631**	**0.013**
Greater Gabbard	**Windfarm**	**2.260**	**0.001**	**998**	**0.001**
	Nearfield Windfarm	1.316	0.05	994	0.069
	Reference	1.298	0.085	13	0.143
	Cable	1.582	0.037	84	0.063
Gunfleet	**Windfarm**	**2.990**	**0.001**	**999**	**0.001**
	Nearfield Windfarm	1.363	0.068	15	0.154
	Reference	1.242	0.171	6	0.236
	Cable	1.208	0.075	35	0.217

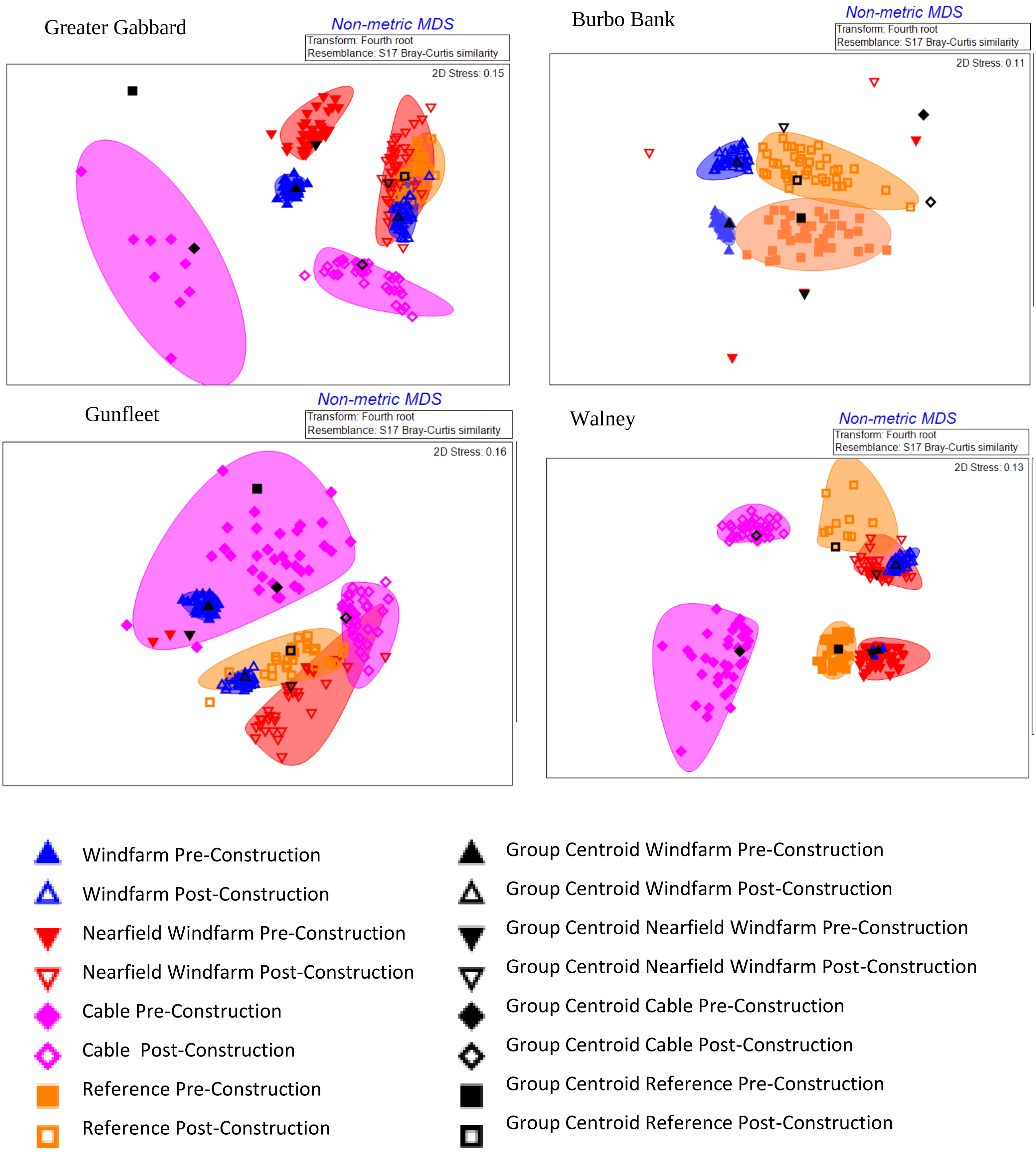

Figure 7 A 2-Dimentional Non-Metric Multi-Dimensional Scaling (MDS) plots of Bootstrap Averages of sample stations pre-wind-farm construction (Filled shapes) and 1 year post construction (empty shapes) within 4 sample types within four windfarms, based on 4th root transformed data and a Bray-Curtis based resemblance matrix A 2D MDS plot represent as Bray-Curtis Dissimilarity matrix in 2-dimensional space, with a data point's distance from all other data points representing its dissimilarity. Points closer together have a greater similarity. Black symbols represent the centre of the sample group, while the coloured polygons represent 95% of the sample variance. note coloured points do not represent individual samples but bootstrapped averages.

3.4.3 Sample Type Level Change in Community Homogeneity

To assess if there was a change in the homogeneity of the samples within each nested group, a Permdisp routine was carried out. This compared average Euclidian distances from group centroids of the nested sample types (Windfarm (sample type(phase))), groups with a greater distance from centroid were considered to be less homogenous. It was found that the mean distance from the group centroid was significantly higher (and thus less homogeneous) in the pre-construction survey than in the post construction survey in the Greater Gabbard 'Windfarm' site type (Pre-Construction mean distance from group centroid = 57.959, Post Construction mean distance from group centroid = 50.467, t = 4.0101,p = 0.002), While the mean distance from centroid was significantly higher in the post construction survey within Walney 'windfarm' site type (Pre-Construction mean distance from group centroid = 31.617, Post Construction = mean distance from group centroid = 37.333, t = 3.6743,p = 0.002 respectively). As there was variation between windfarms regarding significant change it cannot be concluded if the null hypothesis (Hypothesis 4) can be rejected (Figure 8).

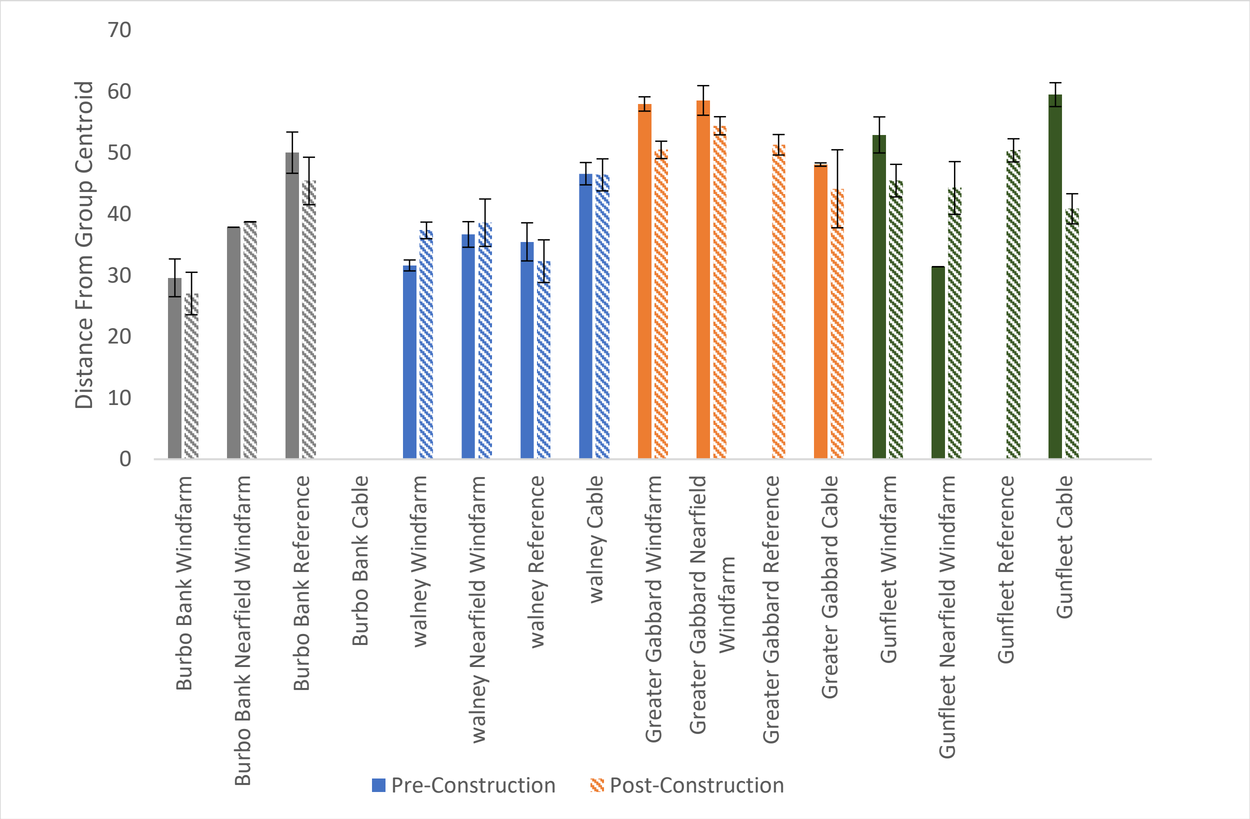

Figure 8 A Bar chart of the output of a PermDisp analysis (which calculates the mean distance from a group centroid within Euclidian space, based on a Bray-Curtis Dissimilarity matrix. (±SE) comparing pre and post windfarm construction within four site types within 4 offshore windfarm developments. A lower value indicates samples in a group have a smaller spread and are more homogenous

Note there is no data for Burbo Bank Cable and Gunfleet and greater gabbard reference preconstruction, this was because only a single station was included in this station, thus there was insufficient data to calculate the means and standard error.

3.4 Windfarm Area Community Change

A SIMPER analysis was carried out on all ‘windfarm’ site types which indicated a significant change, in order to identify change in taxa. taxa which had the greatest contribution to the community change (a cumulative percentage of 20%) were included in this analysis. As seen in tables 6 and 7, each windfarm’s community changed distinctly from the others.

Within the Burbo Bank ‘windfarm’ site type, the bivalve *Spisula subtruncata* recorded an 8.96 decrease in its average abundance, while the bivalve *Donax vittatus* recorded an increase of 13.27 in average abundance. The tube building worm *Lagis koreni* recorded an increase of 58.55 in average abundance, and the bivalve *Kurtiella bidentata* recorded an increase of 28.37 in average abundance (Table 9) these abundance increases were notably higher than the other windfarms.

Within Greater Gabbard, the change in community appeared to be slight, with many species changing in abundance slightly, the polychaete *Lumbrineris cingulata* recorded a 2.86 increase in average abundance. The polychaete *Spirobranchus triqueter* recorded an increase of 1.86 in average abundance (Table 9).

Gunfleet ‘Windfarm’ site type recorded the smallest number of taxa accounting for 20% of the change in community. The key change recorded was a decrease in the average abundance of the amphipod *Bathyporeia pelagica* of 1.13, and an increase in the average abundance of the amphipod *Bathyporeia elegans* of 0.81.

Within Walney, species average abundance changed differently within different site types, the brittle star *Amphiura filiformis* recorded a reduction in average abundance of 4.36 within the ‘windfarm’ site type, and an increase of 6.65 average abundance within the ‘nearfield windfarm’ site type. Similarly, the horseshoe worm *Phoronis* spp. recorded a decrease of 1.32 average abundance within the ‘windfarm’ site type, and an increase of 20.32 average abundance within the ‘nearfield windfarm’ site type. Similarly, to Greater Gabbard the polychaete *Lumbrineris cingulata* recorded an increase in average abundance within both the ‘windfarm’ and ‘nearfield windfarm’ site types of Walney (Table 10).

3.5 IQI Metrics

The IQI calculations involve comparing ecological metrics (AMBI, Simpsons Diversity Index and Species Richness) with theoretical reference conditions dictated by sediment characteristics and salinity. As the construction of the windfarm had the potential to have altered the sediment characteristics in some capacity it was deemed appropriate to carry out the same analytical procedure on each metric independently, as the metric values were calculated prior to applying the reference conditions and thus were independent from any change in sediment, a broad agreement between the metrics and the EQR would add confidence to the EQR results. No significant change was recorded between pre and post construction within any site types within any windfarms thus the null hypothesis (Hypothesis 2) can be rejected, adding confidence to the findings of the EQR results (Figures 9-11).

3.5.1 Cables

While it may appear within Figures 8-10 that a significant change was present within the cable site type, this is not the case, due the low sample numbers within primarily the Pre-Construction cable site type (Table 6) compounded by the non - parametric testing leading to insufficient testing power to identify significant change.

Table 9 The changes to taxa abundance that contributed most to the significant change in benthic community found within Burbo bank, Gunfleet and Greater Gabbard windfarm Site types. Species traits taken from MarLIN, 2006

			Burbo Bank Windfarm Community change					
Species	AMBI	Feeding type	Mobility	Habitat preferences	Percentage Contribution	Cumulative Percentage	Fourth root change	Abundance change
Spisula subtruncata	I	Suspension feeder	Imobile burrower	Fine grained sediment (150-250 um)	4.45	4.45	-1.73	-8.96
Donax vittatus	I	Suspension feeder	Crawler, Burrower	Fine Grained sediment (50-250 µm)	4.16	8.6	1.46	13.27
Lagis koreni	IV	Deposit feeder	burrower	Muddy sand/sandy mud	3.98	12.59	0.53	58.55
Kurtiella bidentata	III	Suspension /deposit feeder	Crawler/burrower	Fine Gravel-muddy sand	3.05	15.63	0.39	28.37
Magelona johnstoni	I	Deposed feeder	Burrower	fine sediments (150 to 300 µm)	2.9	18.54	-0.01	-0.17
Ophiuridae indet	II	Suspension, deposit feeder	Epibenthic crawler	Sand and muddy sand	2.7	21.24	1.08	1.36

			Greater Gabbard Windfarm Community Change					
Species	AMBI	Feeding type	Mobility	Habitat preferences	Percentage Contribution	Cumulative Percentage	Fourth root change	Abundance change
Lumbrineris cingulata	II	Predator, Scavinger	Freeliving burrower, crawler	Gravel-muddy sand	2.45	2.45	1.3	2.86
Lagotia viridis	N/A	N/A	N/A	N/A	1.69	4.13	0.55	0.25
Spirobranchus triqueter	N/A	Suspension feeder	Epifaunal sedentay	Hard rock and shell substrate	1.48	5.61	0.87	1.87
Echinocyamus pusillus	I	Deposit feeder	Free living burrower, crawler	Coarse sand and gravel	1.46	7.07	0.02	0.02
Glycera lapidum	II	Predator Scavenger	Swimmer Burrower	Coarse sediment	1.35	8.42	0.11	0.13
Ophelia borealis	I	Deposit feeder	burrower	Clean sand	1.33	9.75	0.2	0.04

Nemertea indet	III	N/A	N/A	N/A	1.3	11.04	0.32	0.70
Spisula elliptica	I	Suspension feeder	Burrlower	Gravel to fine sand	1.21	12.25	0.46	0.04
Notomastus latericeus	III	Deposit feeder	Free living burrowers	Clean, muddy sand	1.2	13.45	0.78	0.37
Aspidelectra melolontha	II	Suspension feeder	Encrusting	Shells and rocks	1.19	14.65	0.21	0.11
Glycera oxycephala	II	Predator Scavenger	Swimmer Burrower	Coarse sediment	1.16	15.81	-0.07	-0.01
Nematoda indet	III	N/A	N/A	N/A	1.14	16.95	-0.13	-0.05
Conopeum reticulum	II	Suspension feeder	Encrusting	Shells and rocks	1.12	18.06	0.13	0.04
Electra monostachys	II	Suspension feeder	Encrusting	Shells and rocks	1.11	19.17	0.39	0.10
Sabellaria spinulosa	I	Suspension feeder	Tube/reef building	Rock, cobbles bedrock	1.07	20.24	0.56	0.54
		Gunfleet Windfarm Community Change						
Species	AMBI	Feeding type	Mobility	Habitat preferences	Percentage Contribution	Cumulative Percentage	Fourth root change	Abundance change
Bathyporeia pelagica	I	scavingers	Crawler, swimmer	Fine to medium sand	7.48	7.48	-1.03	-1.13
Nucula nitidosa	I	Deposit feeder	burrower	Fine clean sand, Muddy sand, Sandy mud	6.73	14.21	0.15	0.35
Bathyporeia elegans	I	scavingers	Crawler, swimmer	Fine to medium sand	6.44	20.66	0.95	0.81

Table 10 The changes to taxa abundance that contributed most to the significant change in benthic community found within the Windfarm, Nearfield Windfarm and Cable areas of Walney offshore windfarm development. Species traits taken from MarLIN, 2006

		Walney Windfarm Community Change						
Species	AMBI	Feeding type	Mobility	Habitat preferences	Percentage Contribution	Cumulative Percentage	Fourth root change	Abundance change
Amphiura filiformis	II	suspension feeder, deposit feeder	Free living crawler	Muddy sand, Sandy mud	3.05	3.05	-0.31	-4.36
Kirkegaardia dorsobranchialis	N/A	Deposit feeder	Burrower	mud or muddy sand	2.40	5.44	1.02	1.08
Callianassa spp	III	deposit feeder	Burrower, crawler	sandy mud sediments	2.21	7.66	-0.94	-0.78
Kurtiella bidentata	III	Suspension /deposit feeder	Crawler/burrower	Fine Gravel-muddy sand	2.20	9.86	-0.15	-0.35
Golfingia (Golfingia) vulgaris	N/A	Detritus, deposed feeder	Burrower	muddy sand or gravel	2.03	11.89	-0.86	-0.69
Thysanocardia procera	I	Detritus, deposed feeder	Burrower	muddy sand or gravel	1.91	13.80	0.85	0.52
Abyssoninoe Hibernica	II	N/A	N/A	N/A	1.79	15.59	0.74	0.30
Lumbrineris cingulate	II	Predator, Scavinger	Freeliving burrower, crawler	Gravel-muddy sand	1.66	17.25	0.84	0.50
Amphictene auricoma	I	Deposit feeder	burrower	Muddy sand/sandy mud	1.50	18.75	-0.45	-0.29
Phoronis spp	N/A	Suspension feeder	Burrower, encrusting, boring	Rock-muddy sediment	1.50	20.25	-0.03	-1.32
		Walney Nearfield Windfarm Community Change						
Species	AMBI	Feeding type	Mobility	Habitat preferences	Percentage Contribution	Cumulative Percentage	Fourth root change	Abundance change
Amphiura filiformis	II	suspension feeder, deposit feeder	Free living crawler	Muddy sand, Sandy mud	3.38	3.38	0.35	6.65
Lumbrineris cingulate	II	Predator, Scavinger	Freeliving burrower, crawler	Gravel-muddy sand	2.35	5.73	1.14	1.69
Kurtiella bidentata	III	Suspension /deposit feeder	Crawler/burrower	Fine Gravel-muddy sand	2.09	7.82	0.26	0.88
Kirkegaardia dorsobranchialis	N/A	Deposit feeder	Burrower	mud or muddy sand	2.00	9.82	0.87	0.57
Golfingia (Golfingia) vulgaris	N/A	Detritus, deposed feeder	Burrower	muddy sand or gravel	1.94	11.76	-0.83	-0.47
Phoronis spp	N/A	Suspension feeder	Burrower, encrusting, boring	Rock-muddy sediment	1.91	13.67	0.62	20.32
Thysanocardia procera	I	Detritus, deposed feeder	Burrower	muddy sand or gravel	1.84	15.51	0.84	0.50

Thyasira flexuosa	III	Sus-pen-sion feeder	Burrower	mud, muddy sand	1.83	17.34	-0.6	-1.01
Corystes cassivelaunus	I	Scavinger, preditor	Burrower, walker,	sand	1.71	19.05	0.75	0.32
Hyala vitrea	I	deposed feeder	Burrower	N/A	1.62	20.67	0.42	0.58
		Walney Cable Community Change						
Species	AMBI	Feeding type	Mobility	Habitat preferences	Percentage Contribution	Cumulative Percentage	Fourth root change	Abundance change
Magelona mirabilis	I	deposed feeder	Burrower	Coarse clean sand, Fine clean sand	2.74	2.74	-1.12	-2.07
Lagis koreni	IV	Deposit feeder	burrower	Muddy sand/sandy mud	2.56	5.31	1.18	1.94
Nucula nitidosa	I	Deposit feeder	burrower	Fine clean sand, Muddy sand, Sandy mud	2.43	7.74	-0.53	-6.22
Abra alba	III	Suspension and deposed feeder	Burrower	muddy fine sand or mud	2.14	9.88	0.86	0.55
Spiophanes bombyx	III	Suspension and deposed feeder	Burrower	clean sand	2.07	11.95	0.76	1.35
Sthenelais limicola	II	N/A	N/A	N/A	2.01	13.96	0.74	0.75
Magelona johnstoni	I	Deposed feeder	Burrower	fine sediments (150 to 300 µm)	1.91	15.86	0.78	0.37
Corystes cassivelaunus	I	Scavinger, preditor	Burrower, walker,	sand	1.65	17.51	0.64	0.47
Fabulina fabula	I	Suspension and deposed feeder	Burrower	fine to medium sand and silty sand	1.62	19.13	-0.03	-0.03
Phoronis spp	N/A	Suspension feeder	Burrower, encrusting, boring	Rock-muddy sediment	1.57	20.70	0.16	0.11

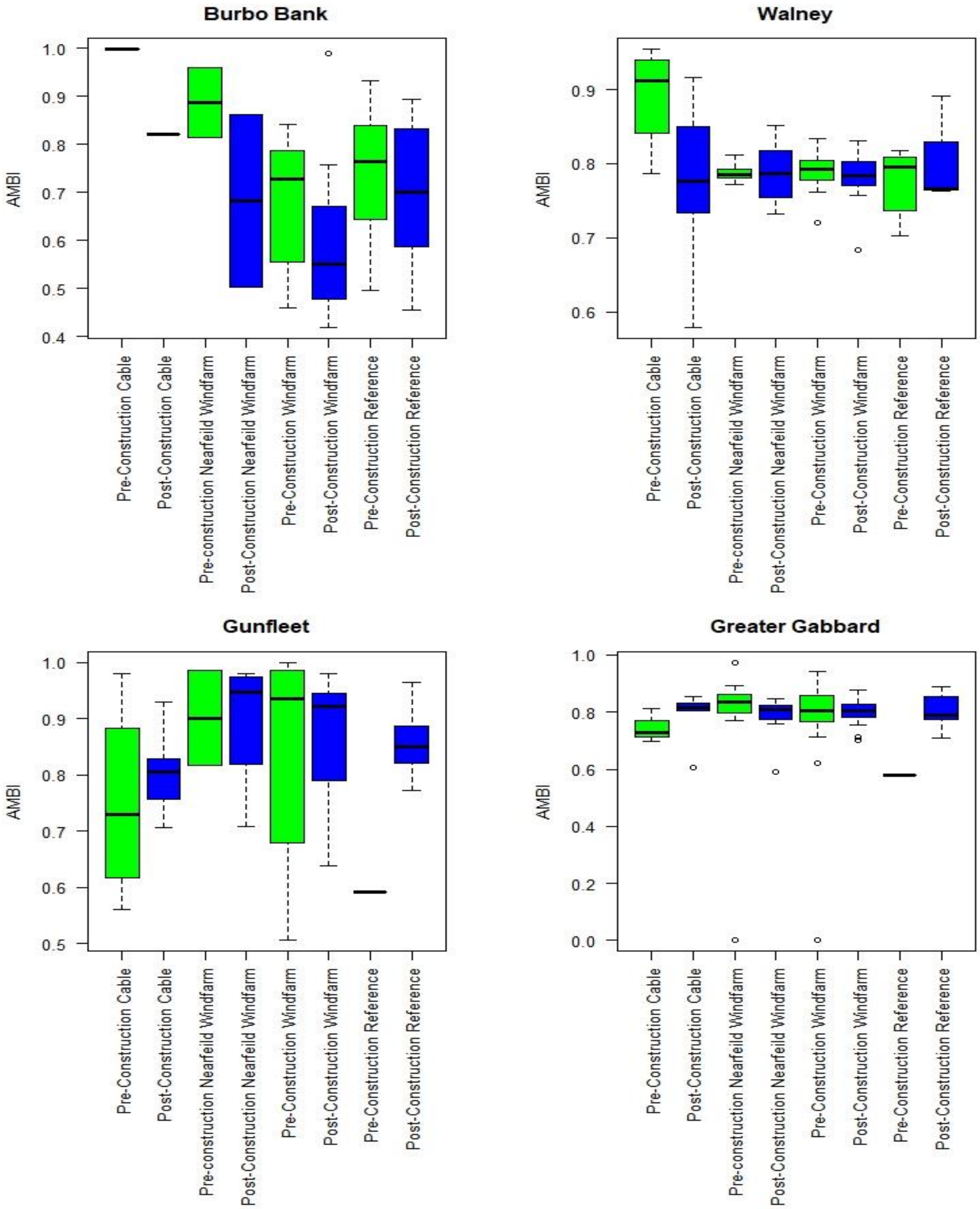

Figure 9 Boxplots showing the difference in AMBI of benthic communities surveyed pre windfarm construction and 1 year post construction within 4 site types within 4 offshore windfarm developments (Burbo Bank, Walney, Gunfleet and Greater Gabbard). A Boxplot represents the spread of data within a distinct category, the bold line indicates the median value, the box represents the upper and lower quartiles, the outside lines represent the minimum and maximum values without outliers (defined as a data point that is outside 1.5 times the interquartile range above the upper quartile and bellow the lower quartile).

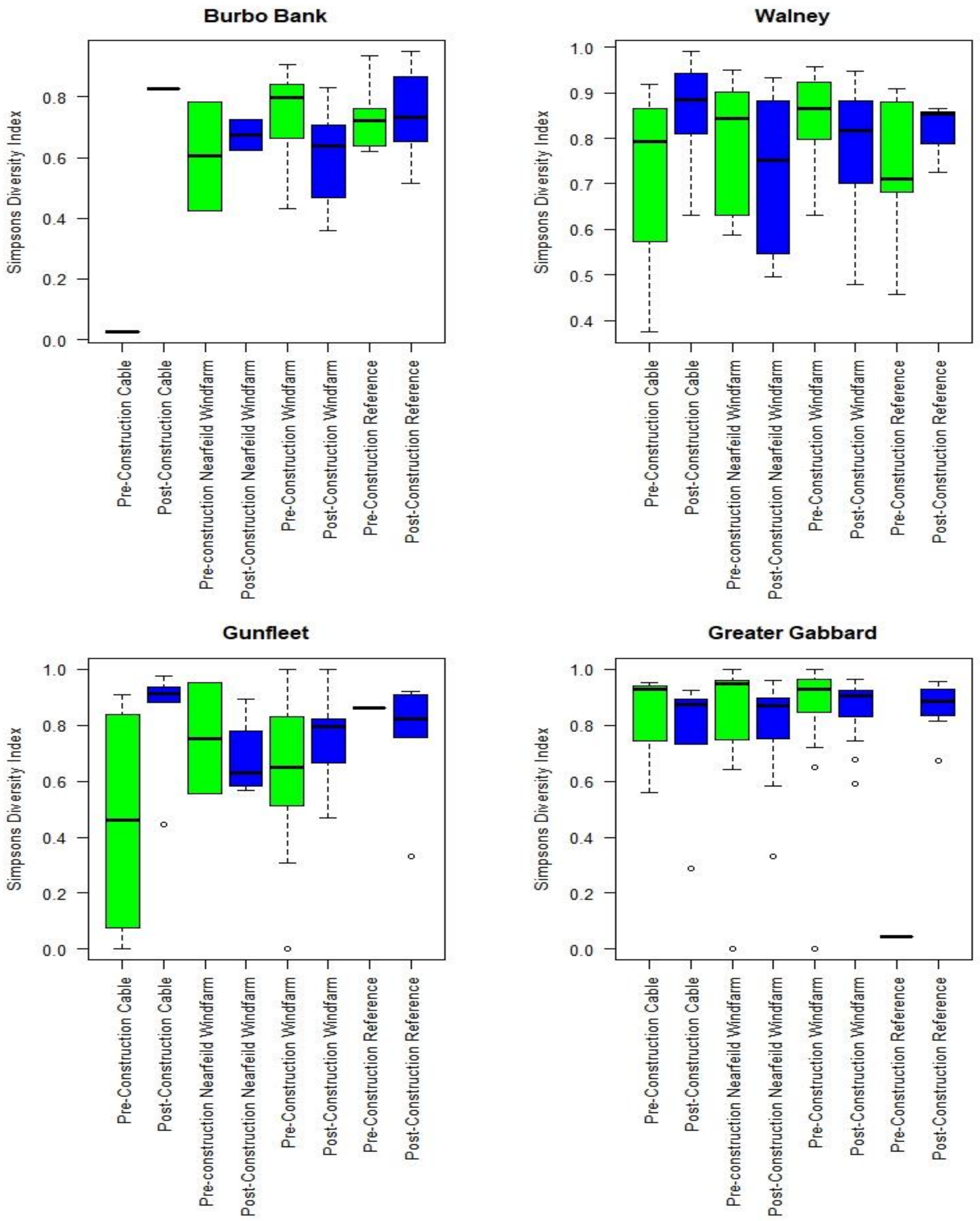

Figure 10 Boxplots showing the difference in Simpsons Diversity Index of benthic communities surveyed pre windfarm construction and 1 year post construction within 4 different site types 4 offshore windfarm developments (Burbo Bank, Walney, Gunfleet and Greater Gabbard). A Boxplot represents the spread of data within a distinct category, the bold line indicates the median value, the box represents the upper and lower quartiles, the outside lines represents the minimum and maximum values without outliers (defined as a data point that is outside 1.5 times the interquartile range above the upper quartile and bellow the lower quartile).

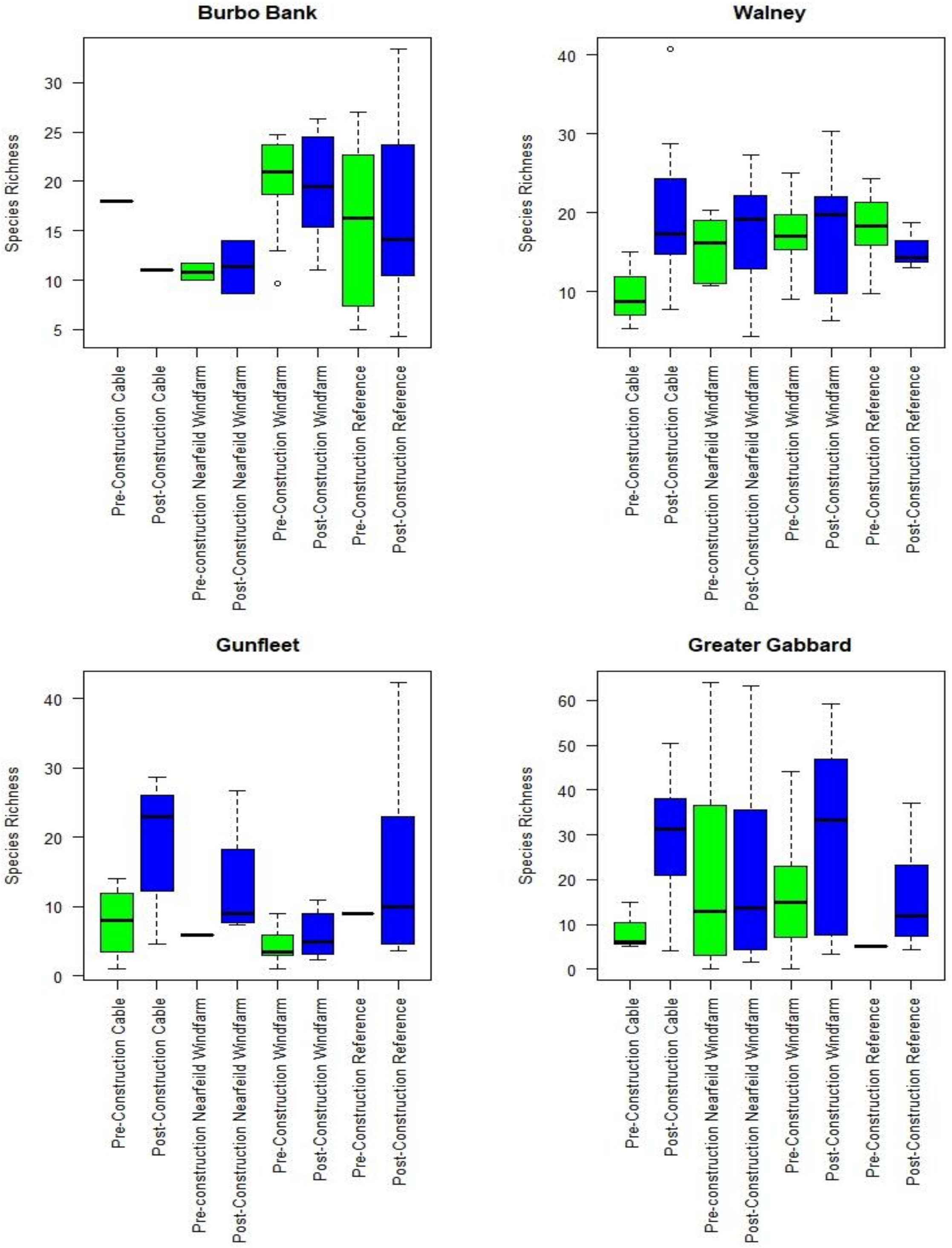

Figure 11 Boxplots showing the difference in Species Richness of benthic communities surveyed pre windfarm construction and 1 year post construction within 4 different site types within 4 offshore windfarm developments (Burbo Bank, Walney, Gunfleet and Greater Gabbard) A Boxplot represents the spread of data within a distinct category, the bold line indicates the median value, the box represents the upper and lower quartiles, the outside lines represents the minimum and maximum values without outliers (defined as a data point that is outside 1.5 times the interquartile range above the upper quartile and bellow the lower quartile).

3.6 Impact of the Sediment Environment on the IQI Metrics

As the IQI reference conditions take sediment statistics into calculation, the impact the mean grain size (Phi) and grain sorting (phi) had on the IQI metrics were assessed, in addition to assessing how the sediment parameters differed between pre and post construction.

3.6.1 Species Richness

The effect of mean grain size (phi) and grain sorting on species richness was assessed using a generalised linear model under a Poisson distribution family. Both grain size and sorting had a significant impact on the number of taxa within a sample. It was found that mean grain size (Phi) negatively impacted the number of species found within a sample. As the phi scale is an inverse $\log_2$ of grain diameter (in mm), this finding suggests that as mean grain diameter increased the number of taxa also increased (Estimate = -0.117546, Z value = 017.95, P < 0.001),. Samples with poorer sorted sediment (higher sorting value) had a greater species number than well sorted samples (Estimate = 0.08883, z = 8.671, P < 0.001),(Figure 12). A multiple GLM was carried out to assess if a significant interaction was present between grain sorting and grain sizes impact on Species Richness. There was found to be a significant interaction between grain sorting and grain size, with a negative interaction present, indicating as mean grain size (phi) decreased, the impact of grain sorting on Species Richness increased (Table 11), thus the Null hypothesis (Hypothesis 6) can be rejected.

Table 11 The output from a multiple generalised liner model using a Poisson distribution, to assess the impact grain sorting and mean grain size (Phi) had on benthic Species Richness including the independent variables interaction, using benthic grab data collected from four offshore windfarm developments

	Estimate	SE	z value	P-value
Intercept	2.679	0.052	51.189	< 0.001
Sorting	0.207	0.020	10.162	< 0.001
Mean grain size (phi)	-0.047	0.017	-2.744	0.006
Interaction	-0.029	0.006	-4.747	< 0.001

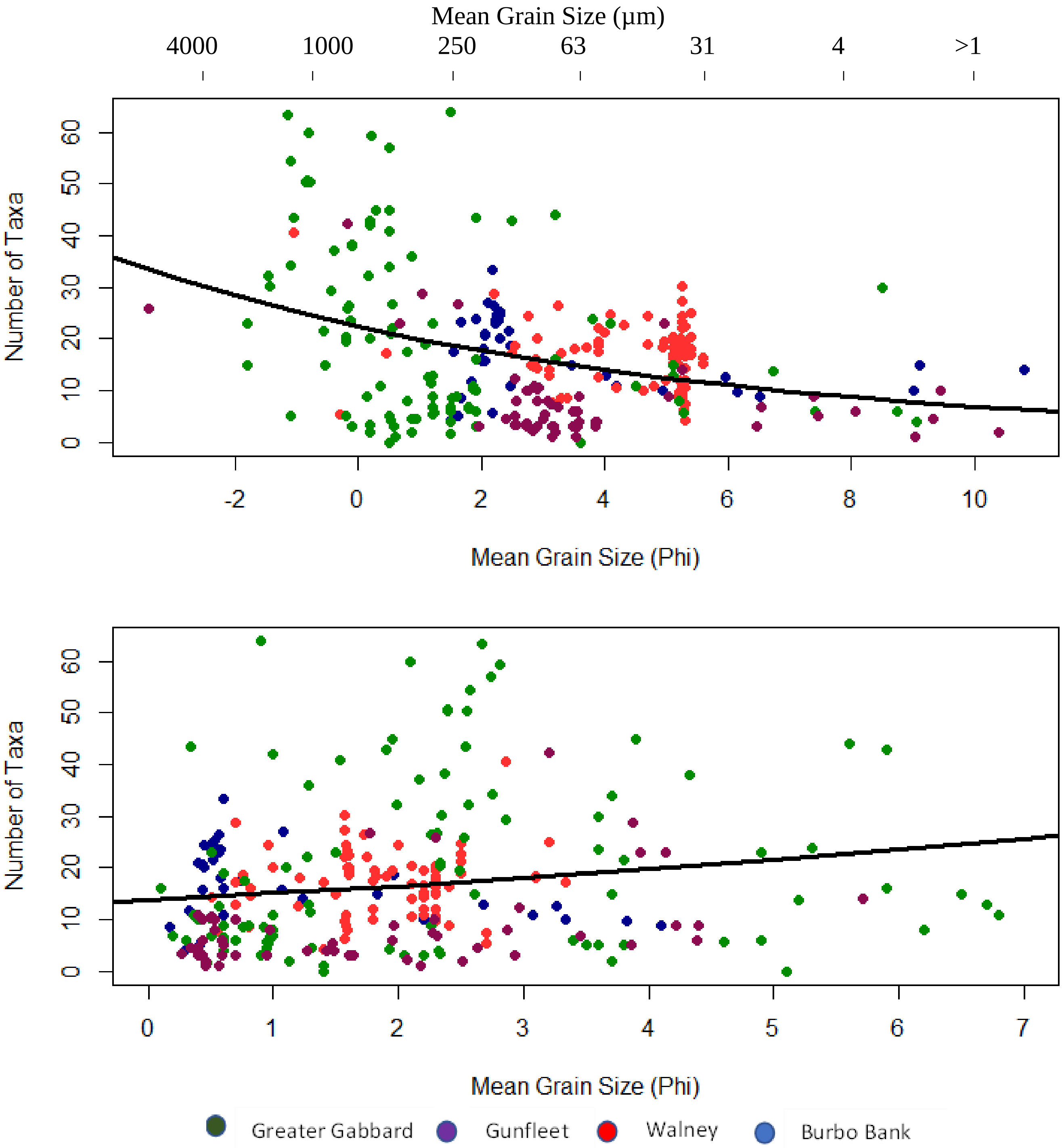

Figure 12 A: Scatterplot of Mean grainsize (Phi), and the Number of taxa found within benthic grab samples within 4 windfarms (Burbo Bank, Walney, Gunfleet and Greater Gabbard). Data was collected during preconstruction and 1 year post construction surveys. The trendline the output of Generalised Linear Model (GLM) based on a Poisson distribution family. Phi is calculated as -Log$_2$ (Grain diameter (mm)).

B: Scatterplot of grain sorting (Phi) and the Number of taxa found within benthic grab samples within 4 windfarms (Burbo Bank, Walney, Gunfleet and Greater Gabbard). Data was collected during preconstruction and 1 year post construction surveys. The trendline the output of Generalised Linear Model (GLM) based on a Poisson distribution family. The sorting value is a derivative of standard deviation thus lower values indicate a more well sorted sediment

3.7 Impact of the Sediment Environment on the Benthic Community

In order to assess how the sediment characteristics impacted the benthic community assemblage, first a RELATE routine was carried out, which uses Spearman's rank correlations of the Bray Curtis based community resemblance matrix and the Euclidean distance based environmental resemblance matrix and aims to assess if the two matrices match. When this was carried out it was found that the sediment environment and community were correlated (Rho = 0.311, p = 0.001). Following this a DistLM routine was carried out. It was found that both mean grain size (phi) and grain sorting had a significant impact on the benthic communities (Pseudo F = 17.545, p = 0.001 and Pseudo F = 6.0575, p = 0.001 respectively). It was found that grain size explained most of the variation ($R^2 = 0.062$) though still a low R^2 value. Sorting had an R^2 of 0.030, with a combined R^2 of 0.091 thus the Null hypothesis (Hypothesis 7) can be rejected. While the effect these sediment characteristics had on the community assemblage were significant, the low combined R^2 indicates that there are other factors which will have likely had a greater impact on the assemblage which were not considered in this analysis.

3.8 Impact of Wind Farms on Sediment Characteristics

3.8.1 Mean Grain Size

There was a significant difference in mean grain size between windfarms (K W chi squared 60.712, df = 3, P < 0.001). A Dunn's non-parametric post hoc test was carried out using Bonferroni corrections to identify significantly differences between windfarms. All windfarm pairs were significantly different from each other apart from Burbo Bank and Greater Gabbard, and Gunfleet and Walney (Figure 13, Table 12) Generally Gunfleet and Walney had finer muddier sediment, while Burbo Bank and Gunfleet had larger grain more sandy sediment. Burbo bank and Walney had the smallest variation in mean grain size, while Gunfleet had a comparably large variation in grain size.

The difference in mean grain size (Phi) between pre and post construction varied between windfarm and site type. Within Greater Gabbard and Gunfleet, the median grainsize (Phi) generally decreased between pre and post construction, while within Walney and Burbo Bank grain size appeared more variable (Figure 14). Pairwise

Wilcoxon tests were carried out using the method described in section 3.3. It was found that there was a significant difference in mean grain size within the ‘windfarm’ site type within Gunfleet alone (W = 0, p value < 0.001) (Table 13) As there was variation between windfarms regarding significant change it cannot be concluded if the null hypothesis (Hypothesis 5) can be rejected.

Table 12 Output from a Dunn's post-hoc comparison test using Bonferroni adjustments, comparing the sediment mean grain size (phi) values of four offshore windfarms developments during preconstruction surveys

Comparison	Z	P. unadjusted	P. adjusted
Burbo Bank – Greater Gabbard	1.933	0.053	0.320
Burbo Bank - Gunfleet	-2.995	0.003	**0.016**
Greater Gabbard - Gunfleet	-5.811	**< 0.001**	**< 0.001**
Burbo Bank - Walney	-3.508	**< 0.001**	**0.003**
Greater Gabbard - Walney	-6.945	**< 0.001**	**< 0.001**
Gunfleet - Walney	-0.282	0.778	1.000

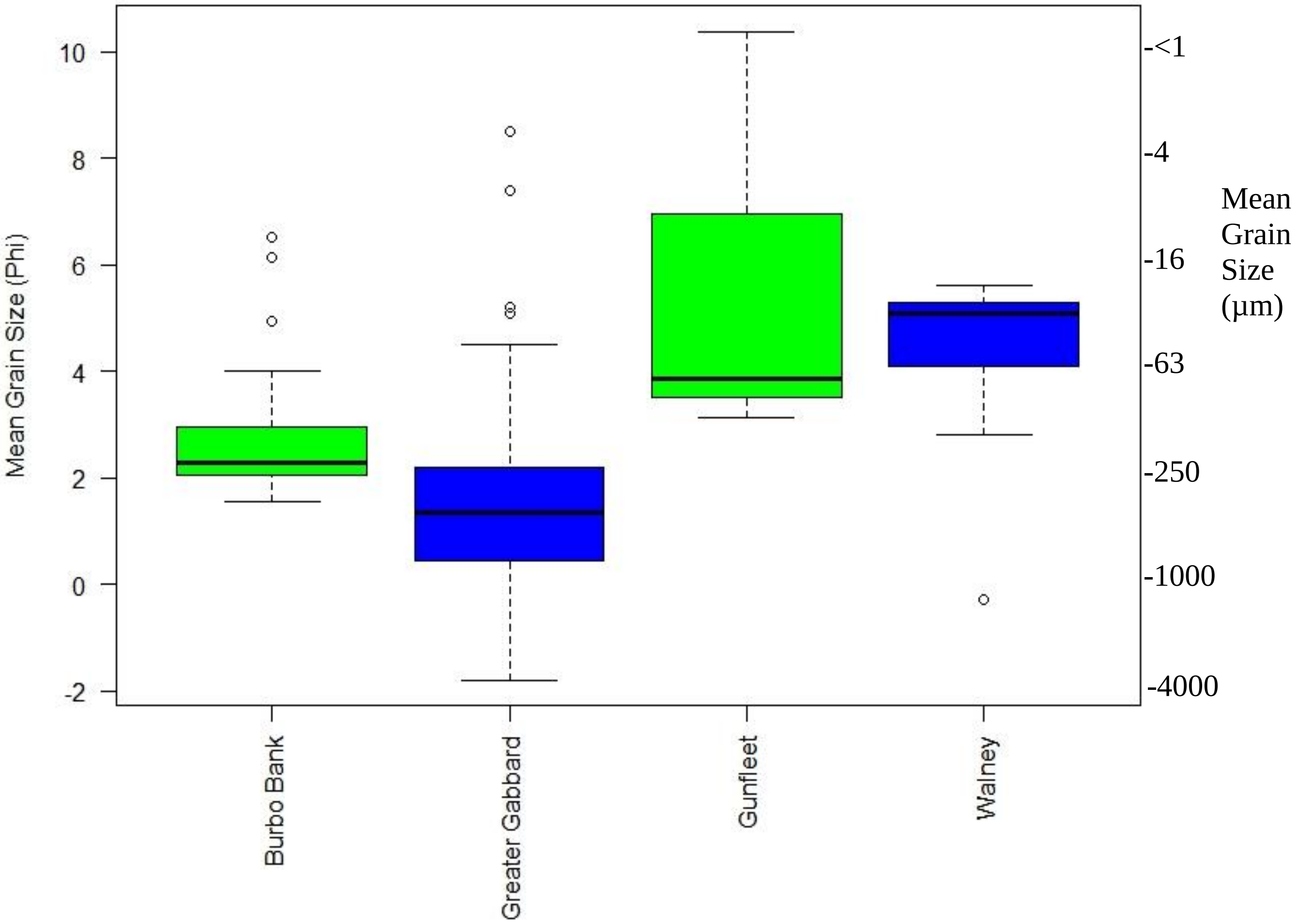

Figure 13 A boxplot showing the difference in mean grain size (Phi) of benthic grab samples collected during pre-windfarm construction surveys within 4 offshore windfarm developments (Burbo Bank, Walney, Gunfleet and Greater Gabbard). A Boxplot represents the spread of data within a distinct category, the bold line indicates the median value, the box represents the upper and lower quartiles, the outside lines represent the minimum and maximum values without outliers (defined as a data point that is outside 1.5 times the interquartile range above the upper quartile and bellow the lower quartile).

Table 13 The outputs of pairwise Wilcoxon Signed rank non-parametric tests of difference in mean grain size (Phi) between pre and post construction within 4 site types within 4 offshore windfarm developments. Significant differences are highlighted in bold. Note due to multiple testing α was set to 0.003 based on a Bonferroni adjustment

Windfarm	**Site**	**Phase**	**Median Mean Grain size**	**W**	**P**
Burbo Bank	Windfarm	Pre-construction	2.311	25	0.312
		Post-Construction	2.233		
	Nearfield Windfarm	Pre-construction	3.398	2	1
		Post-Construction	6.233		
	Reference	Pre-construction	2.146	31	0.95
		Post-Construction	2.083		
	Cable	Pre-construction	2.041	0	1
		Post-Construction	1.867		
Walney	Windfarm	Pre-construction	5.200	174	0.328
		Post-Construction	5.253		
	Nearfield Windfarm	Pre-construction	4.750	29.5	0.516
		Post-Construction	5.229		
	Reference	Pre-construction	3.900	5.5	0.301
		Post-Construction	3.100		
	Cable	Pre-construction	3.050	18	0.829
		Post-Construction	2.810		
Greater Gabbard	Windfarm	Pre-construction	1.200	180	0.006
		Post-Construction	0.363		
	Nearfield Windfarm	Pre-construction	1.500	32	0.066
		Post-Construction	0.570		
	Reference	Pre-construction	-1.100	12	0.154
		Post-Construction	0.544		
	Cable	Pre-construction	-0.200	10	0.905
		Post-Construction	-0.476		
Gunfleet	Windfarm	Pre-construction	3.570	0	< 0.001
		Post-Construction	2.833		
	Nearfield Windfarm	Pre-construction	5.792	0	0.133
		Post-Construction	2.917		
	Reference	Pre-construction	5.047	0	0.235
		Post-Construction	2.733		
	Cable	Pre-construction	8.884	3	0.111
		Post-Construction	1.033		

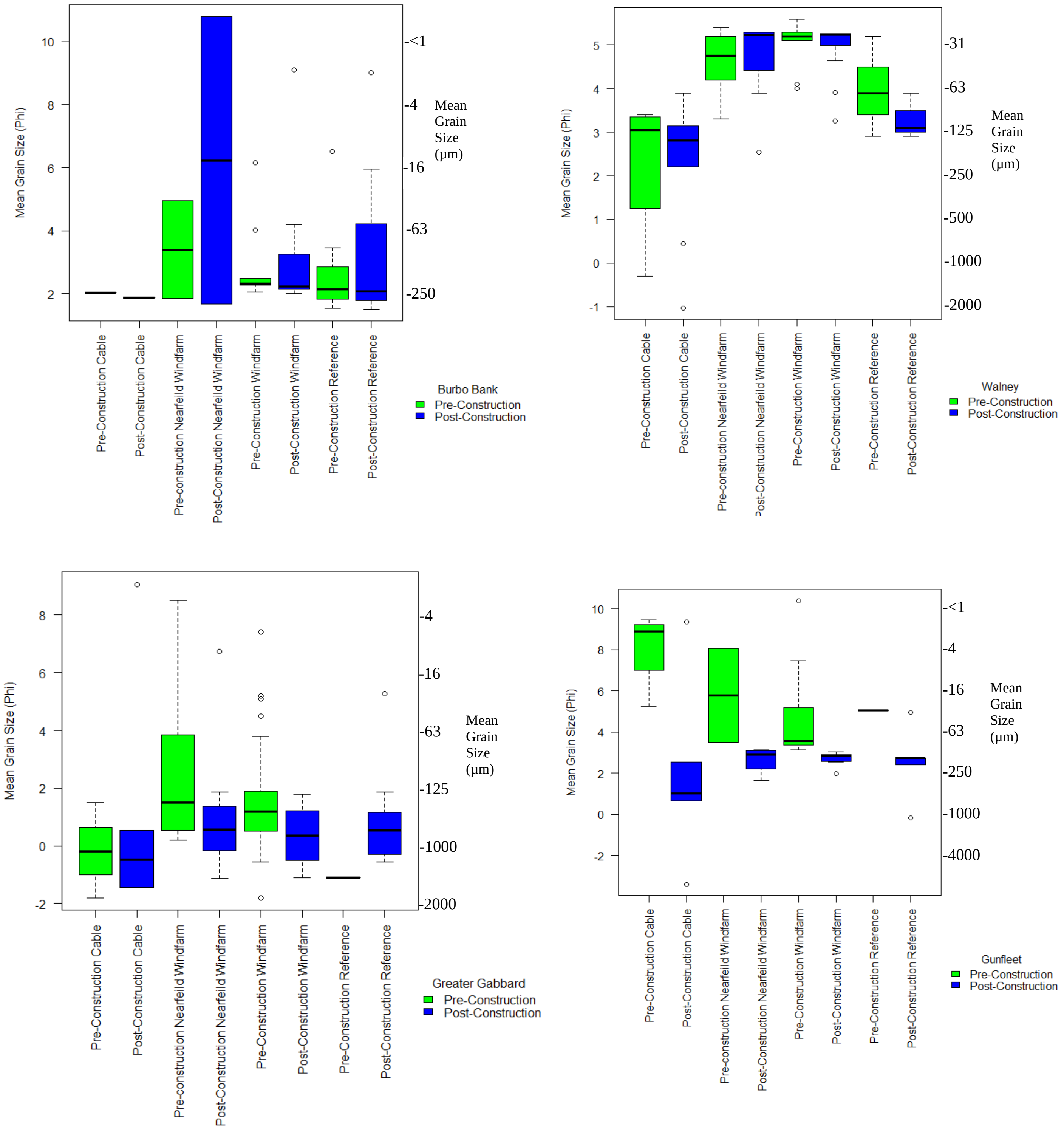

Figure 14 Boxplots showing the difference in mean grains size (Phi) of benthic communities surveyed pre-windfarm construction and 1 year post construction within 4 different site types within 4 off-shore windfarm developments (Burbo Bank, Walney, Gunfleet and Greater Gabbard) A Boxplot represents the spread of data within a distinct category, the bold line indicates the median value, the box represents the upper and lower quartiles, the outside lines represents the minimum and maximum values without outliers (defined as a data point that is outside 1.5 times the interquartile range above the upper quartile and bellow the lower quartile).

3.8.2 Grain Sorting

There was a significant difference in median grain sorting between windfarms (K W chi squared = 12.659, df = 3, p = 0.005). a Dunn's non-parametric post hoc test was then carried out using the Bonferroni method to identify significantly different windfarms. As seen in Table 9, Burbo Bank was significantly different from Greater Gabbard and Walney, all other pairs were not significantly different from each other (Table 14, Figure 15). Similar to grain size, the difference in sorting differed in varied ways between pre and post construction within the different windfarms and site types (Figure 16). A pairwise Wilcoxon test array (see section 3.3) found there was only a significant change in grain sorting within the 'windfarm' site type within Walney (W = 0, p value < 0.001) (Table 15). As there was variation between windfarms regarding significant change it cannot be concluded if the null hypothesis (Hypothesis 5) can be rejected.

Table 14 Output from a Dunn's post-hoc comparison test using Bonferroni adjustments, comparing the sediment grain sorting (phi) values of four offshore windfarm developments during preconstruction surveys

Comparison	Z	P. unadjusted	P. adjusted
Burbo Bank – Greater Gabbard	-2.974	0.003	**0.018**
Burbo Bank - Gunfleet	-2.221	0.026	0.158
Greater Gabbard - Gunfleet	0.567	0.571	1
Burbo Bank - Walney	-3.458	0.001	**0.003**
Greater Gabbard - Walney	-0.699	0.484	1
Gunfleet - Walney	-1.152	0.249	1

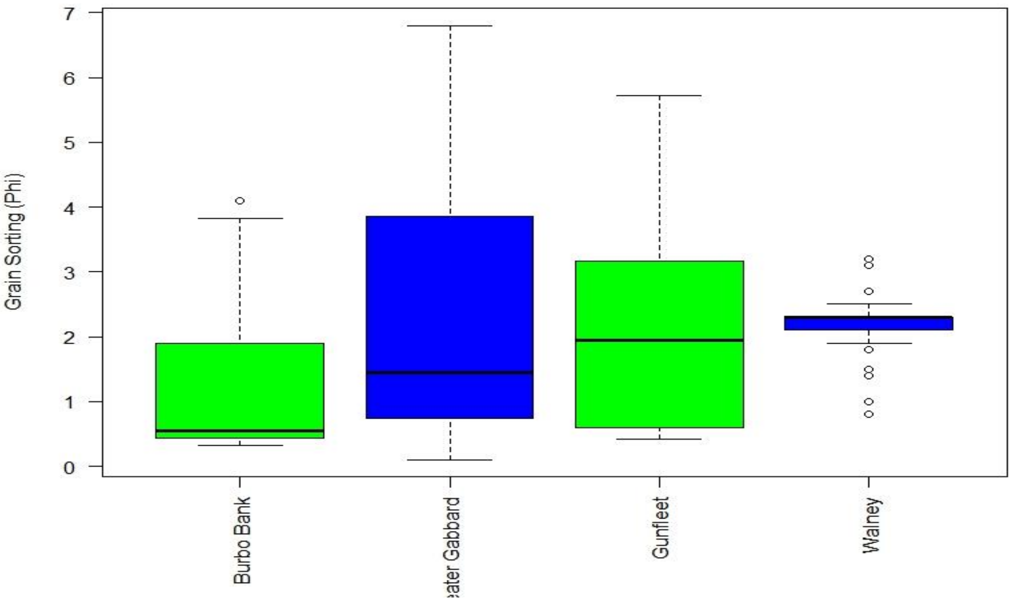

Figure 15 A boxplot showing the difference in mean grain sorting (Phi) of benthic grab samples collected during pre-windfarm construction surveys within 4 offshore windfarm Developments (Burbo Bank, Walney, Gunfleet and Greater Gabbard). A Boxplot represents the spread of data within a distinct category, the bold line indicates the median value, the box represents the upper and lower quartiles, the outside lines represent the minimum and maximum values without outliers (defined as a data point that is outside 1.5 times the interquartile range above the upper quartile and bellow the lower quartile).

Table 15 The outputs of pairwise Wilcoxon Signed rank non-parametric tests of difference in Grain sorting (Phi) between pre and post construction within 4 site types within 4 offshore windfarm developments. Significant differences are highlighted in bold. Note due to multiple testing α was set to 0.003 based on a Bonferroni adjustment

Windfarm	Site	Phase	Median Grain Sorting	W	P
Burbo Bank	Windfarm	Pre-Construction	0.515	47	0.312
		Post-Construction	0.583		
	Nearfield Windfarm	Pre-Construction	1.830	1	0.667
		Post-Construction	0.700		
	Reference	Pre-Construction	0.628	31	0.958
		Post-Construction	0.583		
	Cable	Pre-Construction	0.571	0	1
		Post-Construction	0.400		
Walney	Windfarm	Pre-Construction	2.300	**0**	**< 0.001**
		Post-Construction	1.587		
	Nearfield Windfarm	Pre-Construction	2.150	11.5	0.120
		Post-Construction	1.600		
	Reference	Pre-Construction	2.000	1	0.033
		Post-Construction	0.700		
	Cable	Pre-Construction	1.150	18	0.832
		Post-Construction	0.893		
Greater Gabbard	Windfarm	Pre-Construction	1.100	374	0.425
		Post-Construction	2.156		
	Nearfield Windfarm	Pre-Construction	3.700	38	0.151
		Post-Construction	2.048		
	Reference	Pre-Construction	3.500	1	0.308
		Post-Construction	2.207		
	Cable	Pre-Construction	3.700	8	0.905
		Post-Construction	2.371		
Gunfleet	Windfarm	Pre-Construction	2.371	83	0.027
		Post-Construction	2.371		
	Nearfield Windfarm	Pre-Construction	3.166	1	0.240
		Post-Construction	1.150		
	Reference	Pre-Construction	4.394	0	0.333
		Post-Construction	0.700		
	Cable	Pre-Construction	2.841	12	0.730
		Post-Construction	2.967		

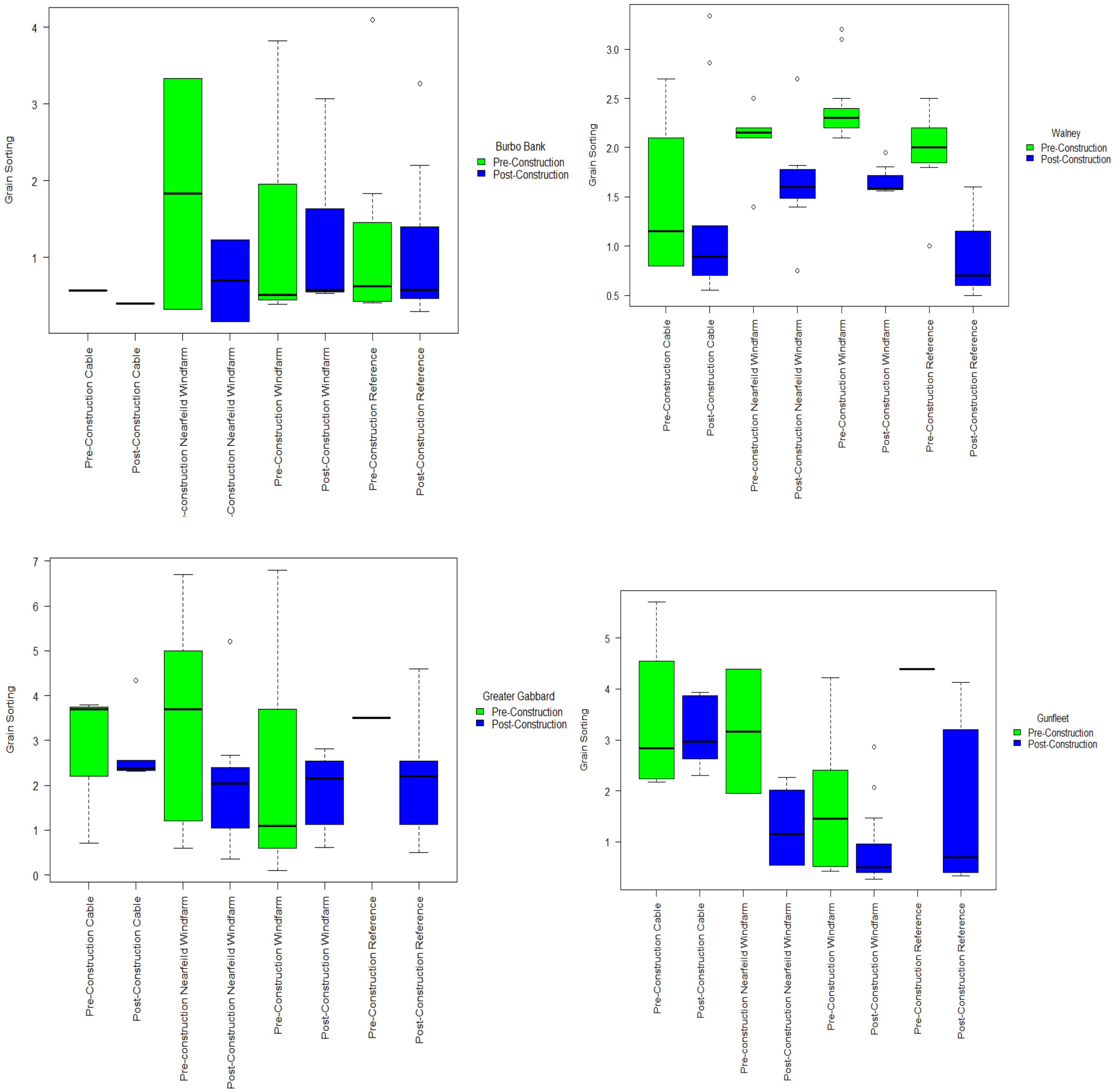

Figure 16 Boxplots showing the difference in grain sorting (Phi) of benthic communities surveyed pre-windfarm construction and 1 year post construction within 4 different Site types within 4 offshore windfarm Developments (Burbo Bank, Walney, Gunfleet and Greater Gabbard) A Boxplot represents the spread of data within a distinct category, the bold line indicates the median value, the box represents the upper and lower quartiles, the outside lines represents the minimum and maximum values without outliers (defined as a data point that is outside 1.5 times the interquartile range above the upper quartile and bellow the lower quartile).

4.0 Discussion

4.1 Summary of Results

No significant changes in average EQR between pre and post windfarm construction were apparent in any site types in any windfarm developments. Conversely, a PERMANOVA routine suggested the benthic community was found to change significantly within the areas classified as ‘Windfarm’ site types in all four windfarm developments. Additionally, the three metrics the IQI is composed of (Species Richness, AMBI and Simpsons Diversity Index) also showed no significant change between pre and post construction. The PermDisp routine indicated that little and variable changes in community homogeneity were apparent between pre and post construction within the four windfarms, this routine can indicate ecological stress where samples within an area (site type) become more homogenous, however this was not apparent in this analysis, so no indication of ecological stress was noted (Chapman et al., 1995; Clarke et al., 2014).

Mean grain size and grain sorting was found to have a significant effect on species richness and the benthic assemblage. Grain size was found to positively impact species richness, with more taxa recorded within samples with a larger mean grain size (samples with a grain size between 1000µm (1mm) and 4000µm (4mm) having between 10 and 70 species, while samples with grain size less that 4µm having between 0-10 species present). A significant interaction between grain size and sorting was apparent with a negative relationship present. Grain size and sorting was also found to significantly affect the community assemblage, however a low cumulative R^2 value indicated that there were many other factors driving the community assemblage which were not included in this study. There appeared to be little difference in the sediment characteristics between pre and post construction within all site types, within all windfarm developments, with variable changes between windfarms and sample types, and the only significant change to grain size found within the ‘windfarm’ site type of Greater Gabbard, and the only significant change in grain sorting found within the ‘windfarm’ site type of Walney.

4.2 The Interaction Between Sediment and Richness

Grain size and sorting had significant but limited impacts on both species' richness and benthic community. Samples with poorer sorted sediment had greater species richness than samples with well sorted sediment . The suggested explanation for this relationship is that poorer sorted sediments have a greater range of grain size habitat complexity and thus an elevated range of niches leading to a greater species richness (Noel Coleman et al., 1997; Ron J. Etter and J. Frederick Grassle, 1992). However, grain size was found to interact with this relationship, with sorting having a smaller impact on Species Richness in samples with smaller average grain sizes, and a greater impact in samples with larger average grain sizes. There are several suggestions why this interaction occurs, within fine mixed sediments, interstitial space is filled with fine silt and mud, while in courser sediments interstitial space is maintained (Gayraud and Philippe, 2003).

Mean grain size also significantly increased species richness, I.e., samples with a larger mean grain size had greater species richness. While this relationship has been identified in other studies, (Coleman et al., 2007; Phillips et al., 2014) it is important to note that this relationship is limited i.e., species richness will theoretically begin to fall at a particular grain size due to limited habitat availability. It is also important to note that grain size and sorting are both linked to the hydrodynamic regime of the area with larger more well sorted sediments found within high energy environments with more mixed poorly sorted sediments found within low flow areas (Chibana et al., 2022; Malvarez et al., 2001). Furthermore, the low R^2 value within the DistLM routine and high degree of variance within the GLMs indicates that there are more dominant factors impacting species richness which may have confounded the analysis, furthermore in depth work is required to fully assess relationships between sediment characteristics and species richness.

Sorting and mean grain size was also found to significantly impact the benthic community. It was beyond the scope of this study to identify community clusters associated to grain size and sorting or to identify any taxa level preferences. However, based on the SIMPER analysis it was apparent that the species *Spirobranchus triqueter* increased in abundance within the Greater Gabbard windfarm area. This species is epifaunal and requires hard substrate such as stone or shell to attach to. This provides possible evidence of a change in sediment size and an increase in the abundance of larger hard substrate Post-Construction having an impact on the benthic community (Chan et al., 2014; Szabó et al., 2014), Additionally larger grain size is and indication of elevated water velocities and thus suspended food. This is known to increase the abundance of suspension feeders (Gili And Coma, 1998), however included in the SIMPER analysis did not indicate trends in suspension feeder abundance.

4.3 Sediment Change

Grain size was only found to significantly increase within the windfarm area at Gunfleet, while sorting was only found to significantly decrease within the windfarm area of Walney. It is interesting that changes in grain size and sorting were each only apparent within one windfarm. However, the lack of apparent change in grain size and sorting within other windfarms is likely a result of the waterbody scope of the analysis leading to acute significant changes being masked by the overall waterbody average. Hydrodynamic models calculated by Rivier et al., 2016 found that water velocity and thus seabed shear force increases at the side of windfarm monopiles, while decreasing in front and behind the monopile. This consequently leads to erosional effects at the sides of monopiles, removing finer sediment and thus increasing average grain size. In addition, the resuspension of finer sediments into the water column can lead to deposition of finer sediments within the surrounding seabed. The scour effect is suggested to impact approximately 50 m each side of a turbine, though this is dependent on monopile diameter and water velocity (Rivier et al., 2016). These models were supported by Page et al., 2019 and Whitehouse et al., 2011 who found scour holes extended < 100 m around the monopile. With regards to depositional effects, resuspended sediments will be deposited within low velocity environments. While it is not possible to comment on the proximity of samples to the monopiles, one suggested reason for the significant increase in mean grain size within Gunfleet is a higher proportion of samples collected within scour effected areas, though further work is required to confirm this.

4.4 Temporal Issues and Walney

The benthic community significantly changed within the ‘windfarm’, ‘nearfield windfarm’ and ‘cable’ site types of Walney. While in the other windfarm developments only ‘windfarm’ site types were found to have a significant change in community. A hypothesised reason for this is the month in which the surveys were carried out. Both pre and post construction surveys were carried out in the same season within Burbo Bank and Gunfleet (September-October and May respectively). Greater Gabbards pre-construction surveys took place in June and November while the post construction surveys took place in May. Walney’s preconstruction surveys took place in April and May, while the post construction surveys took place in December and January. Additionally, when the number of juvenile taxa were compared between the two surveys it was found that Walney post construction survey contained 846 juvenile taxa, while the preconstruction survey only contained 195 juvenile taxa. It is generally understood that benthic community composition fluctuates seasonally (Bae et al., 2018; De Mesel et al., 2015). With the key drivers being seasonal availability of nutrients and detritus (Kelaher and Levinton, 2003) and differing taxon spawning and settling times (Fernandes et al., 2012; Omelyanenko & Kulikova, 2011). It is suggested that this natural seasonal change in community contributed to the observed change in community within Walney’s sites.

4.5 Explanation for Detected Changes in Community That Were Not Visible in the IQI

No significant change in EQR was apparent within any windfarm within any area. While this is unexpected: While it was predicted the piledriving of the monopiles, addition of scour protection, laying of cables and change in hydrodynamic regime, and resuspension of sediment would have lowered the EQR by removing sensitive taxa, and allowing opportunistic taxa to dominate and therefore lowering the number of taxa within the area. It is acknowledged that much of the impacts reported in the literature, are contained to a relatively small area however, it was considered that the cumulation of all pressures may have elicited a waterbody IQI change (Page et al., 2019, Willsteed et al., 2017).

Conversely, benthic communities were found to change significantly at each site. The SIMPER analysis revealed many taxa which displayed a decline in average abundance were within AMBI group I (most sensitive to disturbance) (table 6 and 7). However, other AMBI group I taxa were found to increase in average abundance (table 6 and 7). One hypothesised explanation for the change in community but not in EQR is that the taxa present pre-construction persists post construction, though in different compositions. Thus, a decrease in one taxon may have been masked by an increase in another, an example of this can be seen in Gunfleet 'windfarm' site type where *Bathyporeia pelagica* recorded an average decrease of 1.126 individuals per 0.1m^2 sample, while *Bathyporeia elegans* recorded an average increase of 0.815 individuals per 0.1m^2 sample. both species have an AMBI group of I, thus the change in community composition would not be apparent within the AMBI or Species Richness metrics of the IQI. Within the SIMPER analysis it was apparent that the Echinoderm *Amphiura filiformis* contributed to the difference in areas in Walney. While these taxa are included in the infauna, they along with other echinoderms are large, and thus it is unlikely that they were sampled representatively using a grab method. Similarly, *Phoronis spp* (Which also contributed to the change in Walney groups) lives in patchy high abundance groups, which may have led to an apparent significant change in community driven by small scale natural clustering, however this issue would have been minimised by 4th root transforming the data prior to analysis. In future work these taxa should be used with caution or removed from grab analysis.

However, it is more probable that the lack of change within the EQR and metrics as opposed to community change reflects a limitation with the IQI and waterbody analysis methods sensitivity to detect waterbody change within structurally altered waterbodies.

The age of a windfarm has been found to significantly impacts the benthic community on the surrounding seabed within other studies. Coolen et al., 2022 modelled windfarm age against species richness and Simpsons Diversity Index and found windfarm age had a significant non-linear impact on both metrics: both increased slightly up to between 30 and 40 months after which they began to slightly fall. Subtidal epifaunal communities of *Jassa herdmani*, Actiniaria indet. and Tubularia indet. were found to take 1.5 years to develop to peak densities (De Mesel et al., 2015), it is likely at peak density, propagation and thus community spread to the surrounding seabed would be at its greatest, impacting IQI metrics (Norrie et al., 2020). Additionally, faeces and pseudofaeces produced by epifaunal mussel communities have been found to elevate mud content and nutrients on the surrounding seabed, which in turn leads to an elevation of opportunistic taxa (AMBI EGV) thus leading to reduced AMBI values. (Beadman et al., 2004; D'Amours et al., 2008).

Offshore windfarms have been considered to be defacto marine protected areas as the submarine cables and structures make ground fishing methods unsafe and prohibited (Ashley et al., 2014; Börger et al., 2014; Gray et al., 2016; Hooper and Austen, 2014). A meta-analysis by Foden et al., 2010 suggested that soft sediment habitats take less than one year to recover from beam and otter trawling, both methods were conducted within each farm prior to construction based on maps available from EMODnet, 2022. It is therefore suggested that while adequate time was allowed for any recovery of benthic community from bottom fishing within the area to be detected, insufficient time was allowed for the possible 'spill over effects' of the monopile epifaunal community to spread onto the surrounding benthos. There is potential evidence for this effect as the epifaunal polychaete *Spirobranchus triqueter* increased in abundance between pre and post construction, though no formal analysis on this matter was conducted.

Regarding inter-windfarm differences, it can be noted that Burbo Bank and Gunfleet have lower median EQR values than Walney and Greater Gabbard, a suggested reason for this is that both Burbo Bank and Gunfleet are closer to land than Walney and Greater gabbard, additionally, they are close to major estuarine ports, Burbo is adjacent to the Mersey, While Gunfleet is close to the Thames. It is possible that anthropogenic pressures including pollution and fishing arising from land and river outputs impacted the closer windfarms more than the windfarms further offshore, though with the information available in this investigation, no conclusions can be suggested.

4.6 Limitations to IQI Analysis to Detect Structural Impacts Within a Waterbody

4.6.1 Reference Conditions

As part of the EQR calculations, each sample metric is compared to a metric reference value which aims to approximate the metric were the sample habitat in a theoretical undisturbed environment. To generate this reference metric, the sample sediment statistics and salinity regime are applied to each sample. The key impacts of windfarm construction on the benthic environment are changes in sediment environments by the addition of erosional scour zones near the monopile; and wider depositional effects (Page et al., 2019; Rivier et al., 2016). These changes in sediment characteristics will change the reference metric, in turn masking any natural change in the metric (i.e., the reference metric for coarser substrates is higher than that of finer substrates, thus an increase in sediment size between two sampling events will increase the reference metric which the sample metric is compared against (Phillips et al., 2014). Though it is probable this issue impacted samples within this analysis, no individual metric (which is calculated before applying the reference condition and thus is independent of environmental change) changed significantly at a waterbody level, suggesting other issues were more important in explaining the lack of change in IQI.

4.6.2 Waterbody Size and Size of Impacted Areas

A waterbody analysis aims to represent the waterbody as a whole, rather than local impacts. As previously discussed, the scour effects, in addition to community shift due to the presence of hard substrate, is relatively localised, impacting only 10s of meters around each turbine monopile (Coates et al., 2014; Murray and Thieler, 2004; Page et al., 2019), while the waterbody area and thus area available for sampling is substantially greater (Coates et al., 2014; Coolen et al., 2022). It is therefore possible that the localised impacts of the wind turbine construction were masked by the abundance of samples from outside the area of effect. Within the four windfarms assessed, the ratio between number of monopiles and windfarm area (m^2) ranged from 1:900 within Burbo Bank to 1: 1782 in Gunfleet. Though due to limited resources, exact monopile location and thus sample proximity could not be assessed.

4.6.3 Metric Selection and Community Change

The IQI is one of approximately 35 benthic quality metrics available to assess benthic quality (Borja et al., 2015), of which 12 are used or considered under WFD regulations(Borja et al., 2009). All metrics are required to assess the “Structure and functioning of aquatic systems” (Article 2, no 21) (European Parliament, 2008; Culhane et al., 2014) A metric used to assess the benthic ecological quality is required to assess the i) abundance of invertebrate taxa (Species Richness in the case of IQI), ii) benthic diversity (Simpsons diversity Index in the case of IQI) and iii) proportion of tolerance/ sensitive taxa (AMBI in the case of IQI) (Borja et al., 2009). Additionally, each metric must include a comparison between collected metric values and reference conditions representing undisturbed conditions (Muxika et al., 2007). Each method varies slightly with varying sub-metrics and reference conditions, and each have benefits and negatives.

While IQI is more conservative in detecting disturbance than other methods such as M-AMBI (i.e. the IQI is more likely to indicate a stressor than M-AMBI) (Fitch et al., 2014). It is possible that the metrics used within the IQI assessment poorly detect the change in benthic community generated by the construction of monopiles and other offshore structures. Coupled with the reference conditions masking the change in habitat at a sample level, it is suggested the IQI metric poorly detects benthic community quality change at a waterbody level where offshore windfarm construction is present. It is likely that one of the other 11 metrics used under the WFD may be more appropriate to deal with physical disturbance generated by windfarm construction. One such metric is the Size Spectra Index (SSI), which is based on the concept that larger taxa are more susceptible to disturbance and thus will reduce in abundance compared to smaller taxa in disturbed sites (Basset et al., 2012). Additionally, rather than comparing a sample value to a habitat derived reference condition as with IQI, SSI compares the value against an upper and lower anchor value (0 and 1 respectively) which will not change with changing habitat. The MSFD assesses a much more extensive number of parameters during its assessments (>600 available within all MSFD assessments), with substantially more benthic indicators considered including those within the WFD, but also indicators of specific taxa, extent of colonial and biogenic taxa, ratios of structurally impacted/unimpacted areas (Teixeira et al., 2016).

Further work should be carried out comparing IQI with the SSI and other WFD and MSFD benthic metrics to identify the most suitable benthic quality metric for habitat altering disturbance.

4.6.4 Multivariate Analysis vs Univariate Metrics

Within this study the IQI was compared to standard multivariate techniques, this was done as multivariate techniques are known to be sensitive to community change. Hewitt et al., 2005 compared multivariate techniques with univariate metrics to assess community health along a stressor gradient based on storm overflow location within an estuary. They concluded that multivariate techniques were more effective than univariate metrics. While these methods are commonly used within Habitats Directive and MSFD assessments, there is limited use within WFD classifications. Due to WFD metrics being required to compare a community to a theoretical reference community, thus within multivariate analysis would require a theoretical community for all possible sediment and salinity combinations. And while this exists to some degree within EUNIS biotope classifications (JNCC, 2022) natural localised community variation would make accurate reference communities unfeasible.

4.7 Impacts on Waterbody Classifications and Heavily Modified Waterbody Designations

The methods and classification models designed to classify WFD waterbody element ecological quality are based on natural waterbodies. However, the WFD also designates some waterbodies as Artificial Waterbodies, which are manmade waterbodies such as reservoirs, and Heavily Modified Waterbodies where the waterbodies hydrogeomorphological characteristics have been significantly altered by humans (Borja et al., 2013), for reasons such as power creation, water storage, navigation, port creation and flood defence (Borja and Elliott, 2007). While the aim is to achieve ‘Good Ecological Status in unmodified waterbodies, within a Heavily Modified Waterbody the aim is to achieve Good Ecological Potential, which is defined as the ecological standard/status if the anthropogenic stressor was removed (Borja and Elliott, 2007).

A stepwise process is carried out to designate Heavily Modified Waterbodies, consisting of 11 steps outlined in (European Commission, 2003) Where a waterbody contains windfarm construction, there will be grounds to complete a Heavily Modified

Waterbody designation assessment due to the likely change in hydrogeomorphological characteristics outlined in this investigation. If the process is followed for a theoretical waterbody containing a windfarm using solely IQI data, then it is possible that the waterbody may be falsely rejected as a Heavily Modified Waterbody, as the assessment will fail to detect ecological change, not due to the lack of an ecological response, but rather the IQI processes inability to detect an ecological response, potentially leading to unrealistic ecological standards goals (European Commission, 2003).
Furthermore, within ‘natural’ waterbodies where windfarms are present but not a significant feature, it is possible that, if that waterbody failed to meet Good Ecological Status, due to the masking affect outlined in section 4.6.1-2, the windfarm would not be identified as a potential Reason for Not Achieving Good and thus may lead to wasted resources or failure to remedy any benthic ecological damage associated with windfarm construction and presence.

Theoretically, if a negative impact was apparent post construction due to physical change, the question is asked what mitigation can be done? While impacts on other habitats and organisms can be mitigated by translocation, habitat restoration and conservation projects, limited mitigation is possible within soft sediment as is governed by multiple large scale environmental factors, coupled with relatively low conservation status, additionally while constant pressure inputs into sediment such as nutrient enrichment and pollution can be identified and reduced, where structural habitat change occurs limited mitigation measures can be put in place once the structures are erected.

4.8 Impacts on windfarm data viability in MSFD.

As this study shows, IQI is not impacted by windfarm construction at a waterbody level. Thus it is suggested that this data may be acceptable to be included in the MSFD IQI assessment. At minimum, the baseline surveys could be included to allow preconstruction pressures such as fishing and aggregates dredging impacts to be included. This would allow a much more extensive expanse of marine areas to be included in the assessment.

4.9 Statistical Power and Sample Number

As suggested in Franco et al 2015, 4 stations with 3 replicates (12 samples) is suggested sufficient to generate an MDES of 50%, with 12 samples needed to identify 50% change in species abundance. If these values are applied to this study it can be seen that only the windfarm areas had sufficient sampling effort to generate an MDES of 50%, this may have lead to incorrect conclusions. Thus it cannot be concluded if the apparent significant change in community in the windfarm compared to the other groups derived from the Permanova analysis is a true difference in impact or if merely the windfarm groups had sufficient sampling power to identify a statistical signal through the noise of natural community variation, while within the other areas insufficient sampling power did not allow any signals present to be distinguished through the natural community noise. The amount of variability is an element which drives the power of a statistical assessment, as seen in figure 5 and 7 Walney had comparably little variation in Brey Curtis Dissimilarity compared to the other three windfarms, this may have contributed to the apparent change between pre and post construction in the other areas. Though no conclusions can be drawn with the current data available.

A Before-After-Control-Impacted paired series (BACI-PS) analysis is widely considered to be the most appropriate method of assessing benthic change in offshore windfarms (Franco et al., 2015), however if the four station, three replicate suggestion is considered, all four windfarm surveys assessed in this paper contain both inconsistency in the number of stations and replicates taken within the reference cites, making comparable analysis to the windfarm area impossible. This is apparent for other surveys assessing offshore windfarms (Franco et al., 2015) making hypothesis testing less robust or impossible within offshore windfarm surveys.

4.10 Limitations to Data

While all attempts were made to ensure the data used within this study were as representative as possible, several limitations to the available data made a more thorough investigation not possible. Within the Gunfleet dataset, the preconstruction samples came from a baseline survey and thus stations only contained single replicate samples compared to the post construction triplicate replicate samples, leading to a greater variance within the data. Furthermore, by mean averaging the samples to station level, it may have increased the number of species found in multiple sample stations compared to single sample stations potentially contributing the apparent differences in the multivariate analysis in Gunfleet.

Gunfleet and Greater Gabbard did not repeat the same sample locations throughout both surveys, with several new sites sampled within the post construction survey. While this would have cast doubt over the results of this analysis with regard to community change, similar outcomes were apparent with regards to community and EQR within all windfarms regardless of sampling location consistency. Similarly, the lack of consistent sample sites made site-specific analysis unviable. However, a WFD waterbody analysis does not require consistent sampling locations, only sufficient sample number and spread to represent the whole waterbody (UKTAG, 2014a). Furthermore, while wind turbine point data was available, the cost to acquire the data was too great for this analysis, meaning distance-based regression analysis was not possible. Additionally, it would have been desirable to obtain additional information including biomass, Total Organic Carbon (TOC) and water/sediment chemistry parameters. However, these datasets were inconsistently recorded and thus not available for a full analysis.

4.11 Type I and Type II Errors

With regards to the IQI and metrics, non-parametric statistics were used, as assumptions required for parametric testing were not met. Non-parametric tests are considered less powerful than parametric testing (Kaur and Kumar, 2015; Mumby, 2002; Sedgwick, 2015). Additionally, due to the use of multiple testing, Bonferroni adjustments were applied to the α value, further increasing the conservativeness of the statistics. Therefore, there was an elevated risk of a type II error occurring, where a significant change in EQR or relevant metric was present, however not identified by the suite of statistics (Gordon et al., 2007; Ranganathan et al., 2016).

4.12 Lessons Learned and Improvements

This investigation aimed to assess windfarm constructions impact on the seabed in a way that would as closely resemble a WFD waterbody IQI classification as possible. And while this investigation has identified various limitations with the current waterbody assessment methods used by WFD, it has not been able to identify at what spatial scale any ecological impacts are present. While the metrics and analyses included in this investigation were selected to compare IQI with community change within the scheme of WFD, it is acknowledged that limited analysis was employed to assess specifically how the windfarm construction impacted the benthic community function and structure. Were the aim to specifically assess if and to what extent windfarms cause an ecological response, numerous change would be made to better answer this question.

While species abundance data was used as it could be directly comparable between PRIMER and IQI analyses, however this provides little ecological information, and while ecological information was included in the SIMPER analysis table, it is recommended that if this investigation was assessed to identify how community changed, rather than species data used in the Brey-Curtis and other metrics, the species be split into particular guilds based on size, feeding styles, mobility and other functional traits. This would allow a better understanding of how the community structure changed rather than simply species impacted (Bremner et al., 2006). Furthermore while limited analysis was carried out to assess if the community change was due to an influx of juveniles, it would be beneficial to assess how the season windfarm construction occurs influence the settlement of benthic organisms (De Mesel et al., 2015).

It is acknowledged that this investigation is relatively broad in nature and does not provide in depth analysis on specific links between windfarm construction, distance from monopile, sediment and benthic community. The resolution of the analysis was to mimic a WFD waterbody analysis which does not contain this in depth information. However, if the focus shifted to identify the driving factors, then a shift from waterbody analysis to pressure gradient based distance analysis to provide a better understanding of impact scale.

Additionally the additional confounding variables generated by the inclusion of multiple windfarms made concluding hypotheses challenging: Rather than using four windfarms and averaging the sample data to a station level, a single windfarm should be selected and the triplicate replicates maintained to assess local variability.

Additionally, finer resolution spatial data would be required for location of monopiles and scour protection in order to assess spatial impacts. However, this is not used within a WFD waterbody assessment.

While this assessment focused exclusively on the community change, little investigation was carried out linking particular pressures to community change, and while the only environmental parameter included was sediment statistics there is a wide range of other environmental parameters which could be used to resemble stress, furthermore, while this investigation only focused on the benthic environment, there is current debate that individual habitats should not be looked at within separate silos, rather a holistic analysis is recommended which encapsulates the full ecosystem function in addition to the cumulative effects which offshore wind construction can generate (Willsteed et al., 2017).

5.0 Conclusions

Offshore wind energy projects are predicted to grow in number and scope to meet the twin goals of energy supply and reducing carbon emissions (Kaldellis and Apostolou, 2017; Sadorsky, 2021, 2011). Wind turbine monopiles have been found to have both short and long term effects on local benthic ecology and hydrogeomorphology (Degraer et al., 2020; Kerckhof et al., 2010; Rivier et al., 2016; Whitehouse et al., 2011). Using benthic grab data collected from windfarm monitoring programmes coupled with baseline data available from CEFAS, community analysis and an Infaunal Quality Index (IQI) assessment were conducted for four windfarms at a waterbody level. I found that:

- H6,H7)Sediment characteristics have a significant influence on the benthic community;
- (H5)Sediment mean grain size and sorting showed limited and variable change between Pre-Construction and Post construction;
- (H4) there was limited and variable change in community diversity between pre-Construction and Post construction
- (H3)The benthic community significantly changes between a Pre-Construction baseline state and one year Post-Construction;
- (H1,H2)However, windfarm construction was found to not have a significant effect on the Infaunal Quality Index (IQI), with the hypothesized reasons for the lack of change being:
    i. The reference conditions within the IQI model inadequately handling the change in hydrogeomorphology;
    ii. The waterbody sampling method was too coarse to detect small scale, localised changes associated with wind turbine monopiles.

The IQIs failure to detect change in benthic quality within offshore windfarms, and by extension other human-induced hydrogeomorphologically modified areas, may confound Heavily Modified Waterbody assessments and WFD waterbody investigations where such structures are present, leading to wasted resources and ineffective waterbody management strategies.

It is recommended that further study is required to test the hypotheses regarding limitations to the IQI and waterbody style method. The IQI assessment should be compared against other WFD benthic quality methods to assess if a different metric would be more appropriate to assess changes in hydrogeomorphology. This comparison will need to be at a waterbody level to assess effectiveness within WFD waterbody analysis. Additionally, each metric should be assessed on a spatial gradient with regards to distance and orientation to wind turbine monopiles. Ideally, this comparison should be conducted via a bespoke monitoring program in order to control collected parameters and standardised methodologies. In addition, this program should span multiple years in order to assess if there is a successional change in IQI assessments as monopiles age. With our coastlines and shallow seas undergoing increasing levels of development, it is vital management and monitoring are appropriate to legislative requirements. This suggested programme of work would ensure that current and future waterbody benthic monitoring provides accurate results, allowing us to properly determine the ecological quality of our marine systems under increasing anthropogenic stress.

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Appendix 1

R script

Box 1: A Comparison of EQR's between the four windfarms using preconstruction data : Note the same process was carried out for grain sorting and grain size however without the 'abline' in the boxplot

```
attach(Dataset)
```

when carrying out tasks, R will use data from the dataset

```
kruskal.test(Average_of_IQI[phase=="Pre"]~Windfarm[phase=="Pre"])
```

carry out a Kruskal Wallis test using only 'Pre' construction data

```
dunnTest(Average_of_IQI[phase=="Pre"]~Windfarm[phase=="Pre"], data=Dataset,  method="bonferroni")
```

Carry out a Dunns post Hoc test applying Bonferroni corrections

```
colors=c(rep("green",1),rep("blue",1))
```

change box colours

```
  boxplot(Average_of_IQI[phase=="Pre"]~Windfarm[phase=="Pre"],las=2,xlab="",ylab="EQR",col=colors,names=c("Burbo Bank","Greater Gabbard","Gunfleet","Walney"))
```

create Boxplot

```
 legend(0.5,11,legend=c("Pre-Construction","Post-Construction"),fill=c("Green","blue"),box.lty=0)
```

Add Ledgend

```
abline(h=0.75,col="blue")
abline(h=0.64,col="green")
abline(h=0.44,col="orange")
abline(h=0.24,col="red")
```

Create coloured horizontal lines at set values

```
detach(Dataset)
```

Box 2: the GLMS between Species richness and grain sorting and mean grain size

```
glmspecies richness and phi
attach(dataset)
Sphi<-glm(Average_of_S~Average_of_MEAN_folk_phi,family = poisson(link = log))
Create a GLM  between Species richness (Average_of_S) and mean grain size (Average_of_MEAN_folk_phi) using a poisson distribution family
summary(Sphi)
reveal the output from the GLM
par(mfrow = c(2,1))
create two graphs in the same panel
plot(Average_of_S~Average_of_MEAN_folk_phi,ylab="Number of Taxa",xlab="Mean Grain Size (Phi)")
plot scatterplot
xvalues <- seq(-4, 12, 1)
provide x axis values
yvalues <- predict.glm(Sphi, newdata = list( Average_of_MEAN_folk_phi=xvalues))
predict the trendline of the GLM
lines(xvalues, exp(yvalues), lwd = 3)
Draw trendline
Ssor<-glm(Average_of_S~Average_of_SORTING_folk_phi,family = poisson(link = log))
Create a GLM  between Species richness (Average_of_S) and mean grain sorting (Average_of_Sorting folk phi) using a poisson distribution family
summary(Ssor)
reveal the output from the GLM
plot(Average_of_S~Average_of_SORTING_folk_phi,ylab="Number of Taxa",xlab="Grain Sorting (Phi)")
plot scatterplot
xvalues <- seq(-1, 8, 1)
provide x axis values
yvalues <- predict.glm(Ssor, newdata = list( Average_of_SORTING_folk_phi=xvalues))
predict the trendline of the GLM
lines(xvalues, exp(yvalues), lwd = 3)
Draw trendline
sall<-Ssor<-glm(Average_of_S~Average_of_SORTING_folk_phi*Average_of_MEAN_folk_phi,family = poisson(link = log))
Create a multiple GLM  between Species richness (Average_of_S) and mean grain sorting (Average_of_Sorting folk phi) and Mean Grain Size (Average_of_MEAN_folk_phi) including an interaction term using a poisson distribution family
summary(sall)
reveal the output from the GLM
```

Box 2: Nested pairwise testing of grain size for pre and post construction within each site type in each windfarm. Below is an example of the nested grain size loop using Burbo Bank as the selected windfarm, the same code was used for other windfarms with the names changed, red text describes each line of codes function.

This same code was used to compute and provide boxplots for grain size (this example), Grain sorting, AMBI, Simpsons Diversity Index and Species Richness

```
Burbo<-subset(Dataset,Windfarm=="Burbo_Bank")
```

Subset full dataset to only include data from Burbo Bank

```
attach(Burbo)
```

when carrying out tasks, R will use data from the ‘Burbo’ subset

```
wilcox.test(Average_of_MEAN_folk_phi[sample_type=="windfarm"]~phase[sample_type=="windfarm"])
wilcox.test(Average_of_MEAN_folk_phi[sample_type=="nearfield_windfarm"]~phase[sample_type=="nearfield_windfarm"])
wilcox.test(Average_of_MEAN_folk_phi[sample_type=="windfarm_reference"]~phase[sample_type=="windfarm_reference"])
wilcox.test(Average_of_MEAN_folk_phi[sample_type=="cable"]~phase[sample_type=="cable"])
```

Carry out Wilcoxon signed rank test for pre and post construction values within the sample types described

```
par(mar=c(15,5,3,3))
```

change graphical parameters

```
colors=c(rep("green",1),rep("blue",1))
```

change box colour within boxplot

```
burbodata<-Burbo
```

rename Burbo subset as ‘burbodata’

```
burbodata$phase<-factor(burbodata$phase,c("Pre","post"))
```

create a factor used in creating graphs

```
boxplot(burbodata$Average_of_MEAN_folk_phi[Windfarm=="Burbo_Bank"]~burbodata$phase[Windfarm=="Burbo_Bank"]*sample_type[Windfarm=="Burbo_Bank"],las=2,xlab="",ylab= "EQR",names=c("Pre-Construction Cable","Post-Construction Cable","Pre-construction Nearfeild Windfarm","Post-Construction Nearfeild Windfarm","Pre-Construction Windfarm","Post-Construction Windfarm", "Pre-Construction Reference","Post-Construction Reference"),col=colors)
```

create Boxplot

```
legend(0.5,11,legend=c("Pre-Construction","Post-Construction"),fill=c("Green","blue"),box.lty=0)
```

Add Legend

```
detach(Burbo)
```

remove Burbo subset from R task

Repeat script for other windfarms

Box 3:Nested pairwise testing of EQR for pre and post construction within each site type in each windfarm. Below is an example of the nested EQR loop using Walney as the selected windfarm, the same code was used for other windfarms with the names changed, red text describes each line of codes function

```
Walney<-subset(Dataset,Windfarm=="Walney")
```

Subset full dataset to only include data from Walney

```
attach(Walney)
```

when carrying out tasks, R will use data from the ‘Walney’ subset

```
wilcox.test(Average_of_IQI[sample_type=="windfarm"]~phase[sample_type=="windfarm"])
wilcox.test(Average_of_IQI[sample_type=="nearfield_windfarm"]~phase[sample_type=="nearfield_windfarm"])
wilcox.test(Average_of_IQI[sample_type=="windfarm_reference"]~phase[sample_type=="windfarm_reference"])
wilcox.test(Average_of_IQI[sample_type=="cable"]~phase[sample_type=="cable"])
```

Carry out Wilcoxon signed rank test for pre and post construction values within the sample types described

```
par(mar=c(15,5,3,3))
```

change graphical parameters

```
colors=c(rep("green",1),rep("blue",1))
```

change box colour within boxplot

```
Walneydata<-Walney
```

rename Walney subset as ‘Walneydata’

```
Walneydata $phase<-factor(Walneydata $phase,c("Pre","post"))
```

create a factor used in creating graphs

```
boxplot(Walneydata$Average_of_IQI[Windfarm=="Walney"]~ Walneydata$phase[Windfarm=="Walney"]*sample_type[Windfarm=="Walney"],las=2,xlab="",ylab= "EQR",names=c("Pre-Construction Cable","Post-Construction Cable","Pre-construction Nearfeild Windfarm","Post-Construction Nearfeild Windfarm","Pre-Construction Windfarm","Post-Construction Windfarm", "Pre-Construction Reference","Post-Construction Reference"),col=colors,main="Walney")
```

create Boxplot

```
legend(0.5,11,legend=c("Pre-Construction","Post-Construction"),fill=c("Green","blue"),box.lty=0)
```

Add Legend

```
abline(h=0.75,col="blue")
abline(h=0.64,col="green")
abline(h=0.44,col="orange")
abline(h=0.24,col="red")
```

Create coloured horizontal lines at set values

```
detach(Walney)
```

remove Walney subset from R task

Repeat script for other windfarms

Appendix 2

Species list including AMBI Values

Burbo Bank

	AMBI Value
Cnidaria	
Actiniaria	*I*
Anthoathecata	
Campanulariidae	*I*
Edwardsia claparedii	*III*
Hydractinia echinata	*I*
Phialella quadrata	*I*
Tubularia indivisa	*I*
Nemertea	*III*
Platyhelminthes	*II*
Annelida	
Ampharete lindstroemi	*I*
Aonides paucibranchiata	*III*
Aricidea (Acmira) cerrutii	
Eteone	*III*
Eumida	*II*
Eumida bahusiensis	*II*
Eunereis longissima	*III*
Glycera	*II*
Glycera tridactyla	*II*
Lagis koreni	*IV*
Lanice conchilega	*II*
Magelona filiformis	*I*
Magelona johnstoni	*I*
Magelona mirabilis	*I*
Malmgrenia arenicolae	
Mediomastus fragilis	*III*
Nephtys	*II*
Nephtys assimilis	*II*
Nephtys cirrosa	*II*
Nephtys hombergii	*II*
Oligochaeta	*V*
Ophelia borealis	*I*
Ophelina acuminata	*III*
Owenia fusiformis	*I*
Pholoe baltica	
Phyllodoce groenlandica	
Phyllodoce mucosa	
Phyllodoce rosea	

	AMBI Value
Arthropoda	
Ampelisca brevicornis	*I*
Bathyporeia elegans	*I*
Bathyporeia guilliamsoniana	*I*
Callianassa	*III*
Corystes cassivelaunus	*I*
Crangon allmanni	*II*
Crangon crangon	*I*
Diastylis bradyi	*II*
Diastylis laevis	*II*
Diastylis rathkei	*III*
Gastrosaccus spinifer	*II*
Iphinoe trispinosa	*I*
Liocarcinus	*I*
Liocarcinus holsatus	*I*
Nototropis falcatus	
Nototropis swammerdamei	
Pariambus typicus	*III*
Perioculodes longimanus	*II*
Pinnotheres pisum	
Pontocrates altamarinus	*II*
Portumnus latipes	*I*
Portunidae	
Schistomysis kervillei	*II*
Synchelidium maculatum	*I*
Thia scutellata	*II*
Mollusca	
Abra alba	*III*
Abra prismatica	*III*
Acteon tornatilis	*I*
Asbjornsenia pygmaea	
Chamelea gallina	*I*
Cochlodesma praetenue	
Donax vittatus	*I*
Dosinia	*I*
Ensis	*I*
Ensis ensis	*I*
Ensis magnus	*I*
Euspira nitida	

Pista cristata	*I*
Podarkeopsis capensis	*II*
Poecilochaetus serpens	*I*
Polycirrus medusa	*IV*
Pseudopolydora pulchra	*IV*
Scalibregma inflatum	*III*
Scolelepis bonnieri	*III*
Scoloplos	*I*
Spio decorata	*III*
Spiophanes bombyx	*III*
Sthenelais limicola	*II*

Fabulina fabula	*I*
Goodallia triangularis	*II*
Kurtiella bidentata	*III*
Mactra stultorum	*I*
Mya	*II*
Mytilidae	
Nucula	*I*
Nucula hanleyi	*I*
Nucula nitidosa	*I*
Pharus legumen	*I*
Phaxas pellucidus	*I*
Philine aperta	*II*
Solenidae	*I*
Spisula	*I*
Spisula solida	*I*
Spisula subtruncata	*I*
Tellimya ferruginosa	*II*
Thracia phaseolina	*I*
Varicorbula gibba	
Echinodermata	
Acrocnida brachiata	*I*
Amphiura	*II*
Amphiura filiformis	*II*
Echinocardium cordatum	*I*
Echinocyamus pusillus	*I*
Ophiura	*II*
Ophiura ophiura	*II*
Ophiurida	*II*
Ophiuridae	*II*
Bryozoa	*II*
Alcyonidium	*II*
Conopeum reticulum	*II*
Triticella flava	*II*
Entoprocta	
Pedicellina	
Phoronida	*II*
Phoronis	
Chordata	
Polycarpa fibrosa	*II*

Gunfleet

	AMBI Value
Cnidaria	*I*
Actiniaria	*I*
Anthoathecata	
Cerianthus lloydii	*I*
Edwardsia claparedii	*III*
Eudendrium	*I*
Obelia geniculata	*II*
Phialella quadrata	*I*
Sertularia cupressina	*II*
Nematoda	*III*
Nemertea	*III*
Sipuncula	*I*
Golfingia (Golfingia) elongata	
Annelida	
Ampharete acutifrons	
Ampharete lindstroemi	*I*
Amphicteis midas	*III*
Aonides oxycephala	*III*
Aphelochaeta	*IV*
Aphelochaeta marioni	*IV*
Aphrodita aculeata	*I*
Asclerocheilus intermedius	*III*
Caulleriella alata	*IV*
Chaetozone zetlandica	*IV*
Dipolydora coeca	
Eteone	*III*
Euclymene oerstedii	
Eulalia ornata	*II*
Eumida bahusiensis	*II*
Eunereis longissima	*III*
Glycera alba	*IV*
Glycera tridactyla	*II*
Goniada maculata	*II*
Harmothoe antilopes	*II*
Harmothoe clavigera	
Hilbigneris gracilis	
Lagis koreni	*IV*
Lepidonotus squamatus	*II*
Lumbrineris cingulata	*II*
Magelona johnstoni	*I*
Magelona mirabilis	*I*
Malmgrenia arenicolae	
Marphysa sanguinea	*II*

	AMBI Value
Arthropoda	
Ampelisca spinipes	*I*
Balanus crenatus	
Bathyporeia elegans	*I*
Bathyporeia pelagica	*I*
Corophium volutator	*III*
Corystes cassivelaunus	*I*
Diastylis bradyi	*II*
Diastylis rathkei	*III*
Dyopedos monacanthus	*III*
Haploops tubicola	*III*
Harpinia pectinata	*I*
Perioculodes longimanus	*II*
Photis longicaudata	*I*
Pontocrates altamarinus	*II*
Urothoe poseidonis	*I*
Mollusca	
Abra	*III*
Abra alba	*III*
Abra tenuis	*III*
Barnea candida	
Barnea parva	
Buccinum undatum	*II*
Donax vittatus	*I*
Fabulina fabula	*I*
Kurtiella bidentata	*III*
Limecola balthica	
Musculus discors	*I*
Nucula	*I*
Nucula nitidosa	*I*
Nucula nucleus	*I*
Tellimya ferruginosa	*II*
Varicorbula gibba	
Phoronida	*II*
Phoronis	
Bryozoa	*II*
Alcyonidioides mytili	
Alcyonidium diaphanum	*II*
Anguinella palmata	*II*
Aspidelectra melolontha	*II*
Conopeum reticulum	*II*
Electra monostachys	*II*
Electra pilosa	*II*

Mediomastus fragilis	*III*
Mysta picta	*III*
Nephtys	*II*
Nephtys assimilis	*II*
Nephtys caeca	*II*
Nephtys cirrosa	*II*
Nephtys hombergii	*II*
Nephtys kersivalensis	*II*
Notomastus latericeus	*III*
Ophelia borealis	*I*
Orbinia sertulata	*I*
Pherusa plumosa	*III*
Pholoe inornata	
Podarkeopsis capensis	*II*
Polycirrus	*IV*
Sabellaria spinulosa	*I*
Scalibregma celticum	*III*
Scolelepis bonnieri	*III*
Scoloplos	*I*
Spio armata	*III*
Spiophanes bombyx	*III*
Spirobranchus lamarcki	
Spirobranchus triqueter	
Sthenelais boa	*II*
Escharella immersa	*II*
Schizomavella	*I*
Vesicularia spinosa	*II*
Entoprocta	
Amphipholis squamata	*I*
Echinocardium cordatum	*I*
Echinodermata	
Echinoidea	*I*
Ophiura albida	*II*
Ophiura ophiura	*II*
Ophiuridae	*II*
Pedicellina	
Chordata	
Molgula	*I*

Walney

	AMBI Value
Cnidaria	*I*
Actiniaria	*I*
Anthoathecata	
Anthozoa	
Campanulariidae	*I*
Cerianthus lloydii	*I*
Clytia hemisphaerica	*I*
Edwardsia claparedii	*III*
Phialella quadrata	*I*
Tubularia indivisa	*I*
Virgularia mirabilis	*I*
Nematoda	*III*
Platyhelminthes	*II*
Nemertea	*III*
Cerebratulus	*III*
Sipuncula	*I*
Golfingia (Golfingia) elongata	
Golfingia (Golfingia) vulgaris vulgaris	
Sipuncula	*I*
Thysanocardia procera	*I*

	AMBI Value
Annelida	
Abyssoninoe hibernica	*II*
Ampharete	*I*
Ampharete baltica	*II*
Ampharete falcata	*II*
Ampharete finmarchica	*I*
Ampharete lindstroemi	*I*
Ampharetidae	
Amphictene auricoma	*I*
Ancistrosyllis groenlandica	*III*
Aphelochaeta marioni	*IV*
Aricidea (Aricidea) minuta	
Atherospio	
Chaetozone christiei	*IV*
Chaetozone setosa	*IV*
Chaetozone zetlandica	*IV*
Diplocirrus glaucus	*I*
Eclysippe vanelli	*I*
Eumida bahusiensis	*II*
Eunereis longissima	*III*
Flabelligeridae	
Galathowenia oculata	*III*
Gattyana cirrhosa	*III*
Glycera	*II*
Glycera alba	*IV*
Glycera fallax	*II*
Glycera tridactyla	*II*
Glycera unicornis	*II*
Glyphohesione klatti	*II*
Goniada maculata	*II*
Harmothoe	*II*
Hilbigneris gracilis	
Kirkegaardia dorsobranchialis	
Lagis koreni	*IV*
Lanice conchilega	*II*
Levinsenia gracilis	*III*
Lumbrineris cingulata	*II*
Lumbrineris latreilli	*II*
Magelona alleni	*I*
Magelona filiformis	*I*
Magelona johnstoni	*I*

	AMBI Value
Arthropoda	
Abludomelita obtusata	*III*
Ampelisca brevicornis	*I*
Ampelisca tenuicornis	*I*
Bathyporeia elegans	*I*
Bathyporeia tenuipes	*I*
Bodotria scorpioides	*II*
Callianassa	*III*
Callianassa subterranea	*III*
Corystes cassivelaunus	*I*
Crangon crangon	*I*
Decapoda	
Diastylis bradyi	*II*
Diastylis laevis	*II*
Diastylis rathkei	*III*
Eudorella truncatula	*I*
Goneplax rhomboides	*I*
Harpinia antennaria	*I*
Harpinia crenulata	*I*
Harpinia pectinata	*I*
Ione thoracica	
Jaxea nocturna	*I*
Melita	*I*
Monopseudocuma gilsoni	*II*
Nototropis falcatus	
Nymphon brevirostre	*I*
Paguridae	
Pariambus typicus	*III*
Perioculodes longimanus	*II*
Photis reinhardi	*I*
Pontocrates arenarius	*II*
Portunidae	
Processa nouveli holthuisi	
Pseudocuma (Pseudocuma) longicorne	
Upogebia deltaura	*I*
Mollusca	
Abra	*III*
Abra alba	*III*
Abra nitida	*III*
Acanthocardia echinata	*I*
Chamelea gallina	*I*

Magelona mirabilis	*I*
Malmgrenia andreapolis	
Malmgrenia arenicolae	
Mediomastus fragilis	*III*
Myrianida	
Nephtys	*II*
Nephtys assimilis	*II*
Nephtys caeca	*II*
Nephtys cirrosa	*II*
Nephtys hombergii	*II*
Nephtys incisa	*II*
Nephtys kersivalensis	*II*
Notomastus latericeus	*III*
Ophelia limacina	*I*
Ophelina acuminata	*III*
Owenia fusiformis	*I*
Oxydromus	
Oxydromus flexuosus	
Pectinaria belgica	*I*
Pholoe baltica	
Pholoe inornata	
Phyllodoce	*II*
Phyllodoce maculata	
Podarkeopsis capensis	*II*
Poecilochaetus serpens	*I*
Polycirrus	*IV*
Polynoidae	
Prionospio	
Prionospio cirrifera	
Prionospio fallax	*IV*
Prionospio multibranchiata	
Pseudopolydora pulchra	*IV*
Pygospio elegans	*III*
Scalibregma inflatum	*III*
Scolelepis	*III*
Scolelepis (Scolelepis) foliosa	
Scolelepis bonnieri	*III*
Scolelepis korsuni	*III*
Scoletoma fragilis	*II*
Scoloplos	*I*
Sigalion mathildae	*II*
Sphaerodorum gracilis	*II*
Spio decorata	*III*

Chamelea striatula	*I*
Cylichna cylindracea	*II*
Dosinia	*I*
Dosinia exoleta	*I*
Dosinia lupinus	*I*
Euspira nitida	
Fabulina fabula	*I*
Hyala vitrea	*I*
Kurtiella bidentata	*III*
Mactra stultorum	*I*
Mysia undata	*I*
Nucula nitidosa	*I*
Phaxas pellucidus	*I*
Philine aperta	*II*
Philine quadripartita	
Saxicavella jeffreysi	*I*
Spisula subtruncata	*I*
Tellimya ferruginosa	*II*
Thracia	*I*
Thracia phaseolina	*I*
Thracia villosiuscula	*I*
Thyasira flexuosa	*III*
Varicorbula gibba	
Echinodermata	
Acrocnida brachiata	*I*
Amphiura	*II*
Amphiura chiajei	*II*
Amphiura filiformis	*II*
Astropecten irregularis	*I*
Echinocardium	*I*
Echinocardium cordatum	*I*
Leptosynapta inhaerens	*I*
Oestergrenia digitata	
Ophiura	*II*
Ophiura albida	*II*
Ophiura ophiura	*II*
Ophiuridae	*II*
Paraleptopentacta elongata	
Phoronida	*II*
Phoronis	
Bryozoa	*II*
Alcyonidium parasiticum	*II*
Conopeum reticulum	*II*

Spiophanes bombyx	*III*	*Electra pilosa*	*II*
Spiophanes kroyeri	*III*	*Triticella flava*	*II*
Sthenelais limicola	*II*		
Streblosoma intestinale			
Syllidae			
Terebellides stroemii			

Greater Gabbard

	AMBI Value		AMBI Value		AMBI Value		AMBI Value
Porifera		***Annelida (Continued)***		***Arthropoda***		***Mollusca***	
Cnidaria	*I*	*Lagis koreni*	*IV*	*Abludomelita obtusata*	*III*	*Abra alba*	*III*
Abietinaria	*I*	*Lanice conchilega*	*II*	*Achelia echinata*	*I*	*Abra prismatica*	*III*
Actiniaria	*I*	*Laonice bahusiensis*	*III*	*Ampelisca spinipes*	*I*	*Anomiidae*	*I*
Alcyonium digitatum	*I*	*Leiochone johnstoni*		*Amphilochus manudens*	*II*	*Asbjornsenia pygmaea*	
Anthoathecata		*Lepidonotus squamatus*	*II*	*Anapagurus hyndmanni*	*I*	*Barnea candida*	
Calycella syringa	*I*	*Lumbrineris cingulata*	*II*	*Anapagurus laevis*	*III*	*Barnea parva*	
Campanulariidae	*I*	*Lumbrineris latreilli*	*II*	*Anoplodactylus petiolatus*	*II*	*Buccinum undatum*	*II*
Cerianthus lloydii	*I*	*Lysidice unicornis*		*Anthura gracilis*	*I*	*Calliostoma zizyphinum*	*I*
Clytia hemisphaerica	*I*	*Lysilla loveni*	*II*	*Apolochus neapolitanus*		*Crepidula fornicata*	*III*
Coryne	*I*	*Magelona alleni*	*I*	*Apseudes talpa*	*II*	*Diplodonta rotundata*	*II*
Eudendrium	*I*	*Malmgrenia*		*Atelecyclus rotundatus*	*I*	*Epitonium clathratulum*	*I*
Halecium	*I*	*Malmgrenia arenicolae*		*Axius stirhynchus*		*Euspira nitida*	
Hydrallmania falcata	*I*	*Marphysa sanguinea*	*II*	*Balanus*		*Goodallia triangularis*	*II*
Kirchenpaueria pinnata	*I*	*Mediomastus fragilis*	*III*	*Balanus crenatus*		*Heteranomia squamula*	*I*
Plumularia setacea	*II*	*Myrianida*		*Bathyporeia elegans*	*I*	*Hiatella arctica*	*I*
Sertularia cupressina	*II*	*Nephtys*	*II*	*Bodotria scorpioides*	*II*	*Knoutsodonta depressa*	
Tubularia	*I*	*Nephtys caeca*	*II*	*Callianassa subterranea*	*III*	*Kurtiella bidentata*	*III*
Tubularia indivisa	*I*	*Nephtys cirrosa*	*II*	*Callianassidae*		*Leptochiton asellus*	*I*
Zoantharia	*I*	*Nephtys hombergii*	*II*	*Callipallene*	*I*	*Limacia clavigera*	
Nematoda	*III*	*Nephtys kersivalensis*	*II*	*Caprella septentrionalis*	*II*	*Modiolus*	*I*
Nemertea	*III*	*Nephtys longosetosa*	*II*	*Cheirocratus intermedius*	*I*	*Moerella donacina*	*I*
Platyhelminthes	*II*	*Nereimyra punctata*	*III*	*Diastylis rathkei*	*III*	*Musculus subpictus*	
Sipuncula	*I*	*Nereis zonata*	*III*	*Dyopedos monacanthus*	*III*	*Mysia undata*	*I*
Golfingia (Golfingia) elongata		*Nicolea venustula*	*II*	*Dyopedos porrectus*	*III*	*Mytilidae*	
Phascolion (Phascolion) strombus strombus		*Notomastus*	*III*	*Ebalia*	*II*	*Mytilus edulis*	*III*
Sipuncula	*I*	*Notomastus latericeus*	*III*	*Ebalia tuberosa*	*II*	*Nucula*	*I*
Annelida		*Odontosyllis fulgurans*	*II*	*Ebalia tumefacta*	*II*	*Nucula hanleyi*	*I*
Amaeana trilobata	*I*	*Ophelia borealis*	*I*	*Ericthonius*	*I*	*Nucula nucleus*	*I*
Ampharete lindstroemi	*I*	*Orbinia sertulata*	*I*	*Ericthonius punctatus*	*I*	*Nudibranchia*	
Amphicteis midas	*III*	*Owenia fusiformis*	*I*	*Galathea intermedia*	*I*	*Onchidoris*	*I*
Aonides oxycephala	*III*	*Paradoneis lyra*	*III*	*Gammaropsis maculata*	*I*	*Polititapes rhomboides*	
Aonides paucibranchiata	*III*	*Parexogone hebes*		*Gastrosaccus spinifer*	*II*	*Sphenia binghami*	*I*
Aphelochaeta	*IV*	*Paucibranchia bellii*		*Gyge branchialis*		*Spisula elliptica*	*I*
Aricidea (Aricidea) minuta		*Petaloproctus*	*II*	*Harpinia pectinata*	*I*	*Spisula solida*	*I*

Asclerocheilus intermedius	*III*
Atherospio	
Bathyvermilia langerhansi	
Caulleriella alata	*IV*
Chaetozone zetlandica	*IV*
Clymenura	*III*
Dipolydora caulleryi	
Dipolydora coeca	
Dipolydora socialis	
Drilonereis filum	*II*
Enipo kinbergi	*II*
Eteone	*III*
Euclymene oerstedii	
Eulalia aurea	*II*
Eulalia mustela	*II*
Eumida	*II*
Eumida bahusiensis	*II*
Eumida sanguinea	*II*
Eunereis longissima	*III*
Exogone verugera	*II*
Filograna implexa	*I*
Flabelligera affinis	*II*
Galathowenia oculata	*III*
Gattyana cirrhosa	*III*
Glycera alba	*IV*
Glycera lapidum	*II*
Glycera oxycephala	*II*
Glycinde nordmanni	*II*
Goniada maculata	*II*
Harmothoe	*II*
Harmothoe extenuata	*II*
Harmothoe glabra	
Harmothoe impar	*II*
Hesionura elongata	*II*
Hilbigneris gracilis	
Janua heterostropha	
Jasmineira elegans	*II*
Petaloproctus borealis	
Pholoe baltica	
Pholoe inornata	
Phyllodoce	*II*
Phyllodoce longipes	
Phyllodoce maculata	
Pisione remota	*I*
Podarkeopsis capensis	*II*
Poecilochaetus serpens	*I*
Polycirrus	*IV*
Polycirrus medusa	*IV*
Polygordius	*I*
Polynoe scolopendrina	*II*
Polynoidae	
Praxillella affinis	*III*
Protodorvillea kefersteini	*II*
Protula tubularia	*I*
Psamathe fusca	*III*
Pseudopolydora pulchra	*IV*
Pseudopotamilla reniformis	*II*
Sabellaria spinulosa	*I*
Sabellidae	*I*
Scalibregma celticum	*III*
Scalibregma inflatum	*III*
Schistomeringos rudolphi	*II*
Scoloplos	*I*
Serpulidae	
Sphaerosyllis bulbosa	*II*
Sphaerosyllis taylori	*II*
Spio armata	*III*
Spio decorata	*III*
Spiophanes bombyx	*III*
Spirobranchus	*II*
Spirobranchus lamarcki	
Spirobranchus triqueter	
Sthenelais boa	*II*
Syllidae	
Syllidia armata	*II*
Syllis	*II*
Syllis armillaris	*II*
Hyas	*I*
Hyas coarctatus	*I*
Ione thoracica	
Iphimedia minuta	*I*
Iphimedia spatula	*I*
Janira maculosa	
Leptocheirus hirsutimanus	*III*
Leucothoe procera	*I*
Liocarcinus	*I*
Liocarcinus pusillus	*I*
Maerella tenuimana	
Megamphopus cornutus	
Metopa alderi	*II*
Metopa borealis	*II*
Metopa pusilla	*II*
Monocorophium sextonae	*III*
Mysida	
Nototropis falcatus	
Nototropis swammerdamei	
Nymphon brevirostre	*I*
Othomaera othonis	
Paguridae	
Pagurus	*II*
Pagurus bernhardus	*II*
Pagurus cuanensis	*II*
Pandalidae	
Pandalus borealis	*II*
Pandalus montagui	*II*
Photis longicaudata	*I*
Phtisica marina	*I*
Pilumnus hirtellus	*I*
Pisidia longicornis	*I*
Pseudoprotella phasma	*III*
Stenothoe marina	*II*
Tanaopsis graciloides	*III*
Unciola crenatipalma	*I*
Upogebia deltaura	*I*
Urothoe brevicornis	*I*
Urothoe elegans	*I*
Urothoe marina	*I*
Steromphala tumida	
Thracia	*I*
Timoclea ovata	*I*
Tritia incrassata	
Tritonia hombergii	
Echinodermata	
Amphipholis squamata	*I*
Echinidea	
Echinocardium	*I*
Echinocardium cordatum	*I*
Echinocyamus pusillus	*I*
Leptosynapta inhaerens	*I*
Ophiothrix fragilis	*I*
Ophiura	*II*
Ophiura albida	*II*
Ophiuridae	*II*
Psammechinus miliaris	*I*
Phoronida	*II*
Phoronis	
Bryozoa	*II*
Alcyonidioides mytili	
Alcyonidium	*II*
Alcyonidium diaphanum	*II*
Alcyonidium parasiticum	*II*
Amathia	*I*
Aspidelectra melolontha	*II*
Bicellariella ciliata	*II*
Callopora dumerilii	
Cauloramphus spiniferum	*II*
Cellepora pumicosa	*I*
Chorizopora brongniartii	
Conopeum reticulum	*II*
Crisia	*II*
Disporella hispida	*II*
Electra monostachys	*II*
Electra pilosa	*II*
Escharella immersa	*II*
Escharella variolosa	*II*
Escharella ventricosa	*II*
Hagiosynodos latus	*II*

Syllis cornuta	*II*
Syllis variegata	*II*
Terebellidae	
Terebellides stroemii	
Thelepus	*II*
Thelepus cincinnatus	*II*
Thelepus setosus	*II*
Verruca stroemia	*I*
Brachiopoda	
Gwynia capsula	
Hincksina flustroides	*II*
Hippothoa divaricata	*II*
Hippothoa flagellum	*II*
Microporella ciliata	*II*
Oncousoecia dilatans	
Plagioecia patina	*II*
Porella concinna	*II*
Reptadeonella violacea	*II*
Schizomavella	*I*
Schizoporella	*I*
Scrupocellaria scruposa	*II*
Triticella flava	*II*
Tubulipora	*II*
Turbicellepora avicularis	*II*
Vesicularia spinosa	*II*
Entoprocta	
Pedicellina	